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AUTHOR Waring, Gene
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ABSTRACT

Designed for individualized use in an applied physics course in postsecondary vocational-technical education, this series of ten learning modules is equivalent to the content of a five-credit hour class in automotive technology or diesel technology. Almost all the modules contain technological application in the form of laboratory experiments or as applied homework problems. Each module contains the following components: a cover page explaining the purpose and contents of the module; learning objectives; learning activities; a self-evaluation test with an answer key; and a final test based on the stated objectives. These ten modules are a part of twenty-three applied physics modules which have been developed for use in several technology courses, including architectural and civil drafting, manufacturing engineering, machine tool and design, welding, industrial plastics, electrical, electronic service, electronic engineering, and electromechanical technologies. All twenty-three modules are available in ERIC document CE 014 409. Instructions in the use of the modules, related notes, data sheets, tests, and answer keys are included in a separate document (CE 014 408). (BM)

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ED150313

Applied Physics Modules Selected for Automotive and Diesel Technologies

October 1976

U S DEPARTMENT OF HEALTH, EDUCATION & WELFARE
NATIONAL INSTITUTE OF EDUCATION

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CE 014 412

Southeast Community College--Milford Campus, Milford, Nebraska 68405

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 6

Title: Friction

Module Contents:
1. The nature of friction
2. The coefficient of friction
3. Kinetic and static friction
4. Rolling friction
5. Lubrication

Program: This module was prepared especially for students in:

1. Automotive technology
2. Diesel technology

Purpose: The purpose of this module is to introduce the concept of friction. It is a force that always acts to impede motion. It reduces efficiency of machines and great efforts are made to minimize it by using lubricants and wheels. Sometimes friction is desirable; the action of brakes and clutches depend on it. Friction is an ever present force in almost all automotive and diesel engines and equipment. It is essential that you understand the nature of friction.

Producer: Gene Waring

Date Produced: September 1976

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STUDENT INSTRUCTIONS (T)

Module M 6 FRICTION

OBJECTIVES

When you have completed this module satisfactorily, you will be able to:

1. Define friction, coefficient of friction and normal force.
2. State the laws of friction for dry surfaces.
3. State the mathematical formula relating the force of friction, normal force and coefficient of friction.
4. State the differences between limiting friction and kinetic friction.
5. State two ways in which rolling friction differs from sliding friction.
6. State the effects of lubricants on sliding and rolling friction.
7. List rolling, sliding and fluid friction in order of decreasing friction effects.
8. Solve various frictional problems, including those on an inclined plane, in which the relationships in objective 3 is included.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of measurement. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink paper, page 6) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page).

LEARNING ACTIVITES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. You may want to do most or all of the activities if your overall background requires it. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook and the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to learning them. Also, read the information sheet (A).

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read sections 6.8--6.17 in chapter 6, pages 144-152.

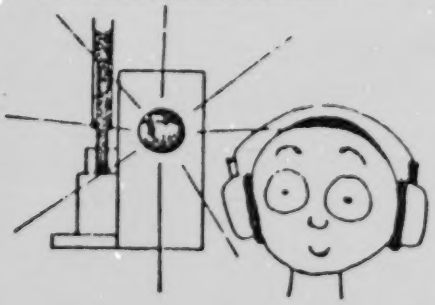
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read sections 3.5--3.9 in chapter 3, pages 30-33.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read sections 10.13--10.17 in chapter 10, pages 142-44. Also read all the information sheets (see A above).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read all of chapter 7, pages 82-90.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read all of chapter 6, pages 78-86.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Rough and Smooth, (EBE S-80781)
B. Texture, (EBE S-80782)
C. Rolling, (EBE S-80783)
D. Wheels, (EBE S-80784)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving equilibrium of riged body problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about sliding friction on horizontal surfaces.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M - 6) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be average to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST (T)

Module M 6 FRICTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The force of friction is proportional to the normal force.

T - F 2. Changing the weight of an object will not change the coefficient of friction between the object and the surface it slides on.

T - F 3. A 195 lb weight on a horizontal surface has a normal force of 117 lb.

T - F 4. Kinetic friction is usually less than limiting friction if everything else remains the same.

T - F 5. Lubricants can reduce kinetic friction but not limiting friction.

6. A 4000 lb automobile requires a force of 3120 lb to cause it to go into a skid. The coefficient of limiting friction between tires and road is:

a) 0.84
b) 1.09
c) 0.78
d) cannot be calculated

7. A force of 250 lb is required to slide a TV set across a tiled floor. If the coefficient of kinetic friction is 0.63, how much does the TV set weigh in pounds?

a) 694
b) 397
c) 157
d) cannot be calculated

8. A crate is pulled along a surface on which the coefficients of limiting and kinetic friction are 0.42 and 0.28. If the crate weighs 1200 lb, what force will keep the crate moving once it is started?

ANSWER KEY TO THE SELF-EVALUATION TEST (T)

Module M 6 FRICTION

Question-Answer	If you missed this question, you are directed to these learning activities
1. T	I. Reading or V. Laboratory Experiments
2. T	I. Reading or V. Laboratory Experiments
3. F	III. Solving Problems or V. Laboratory Experiments
4. T	I. Reading (Information Sheets)
5. F	I. Reading or II. Listening/Viewing
6. c	III. Solving Problems
7. b	III. Solving Problems or V. Laboratory Experiments
8. 336 lb	III. Solving Problems or V. Laboratory Experiments

INFORMATION SHEET

Module M 6 FRICTION

Part I

SLIDING FRICTION

For dry surfaces, friction has been found to obey the following rules:

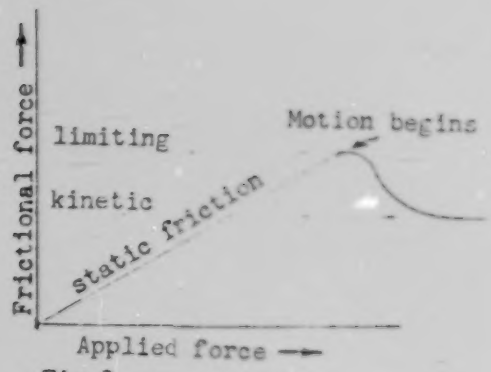


Fig 1

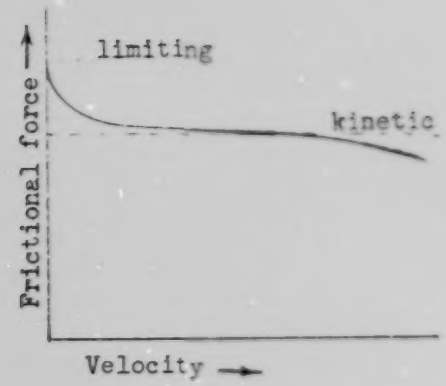


Fig 2

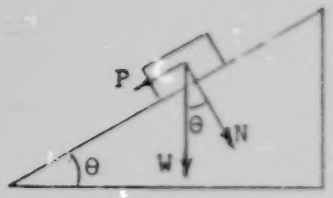


Fig 3

1. The frictional force is equal to the applied force before motion begins (see Fig. 1) and is called static friction.

2. The static frictional force is maximum just before motion begins. The maximum value of static friction is called limiting friction (see Fig. 1). Many texts use the term static friction to mean limiting friction.

3. After motion has begun, friction is usually less than the limiting friction and is called kinetic friction (see Fig. 1).

4. Kinetic friction is nearly independent of speed. It gradually decreases at higher and higher speeds, but the change is slight until extreme speeds are reached (see Fig. 2).

5. Both limiting and kinetic friction depend on the nature of the sliding surfaces.

6. Both limiting and kinetic friction depend on the force pressing the two surfaces together. This force is called the normal force (N) (see Fig. 3). On an incline the normal force is given by the equation:

$$N = W \cos \theta$$

where θ is the angle of the incline and W is the weight of the sliding object. Note that the normal force is the component of the weight that is perpendicular to the incline.

7. The frictional force is independent of the apparent contact area. The distinction between apparent and real contact area is discussed in Part II.

THE COEFFICIENT OF FRICTION

The seven rules above describe how friction works. The source or cause of friction is described in Part II.

Rule 6 states that friction is proportional to the normal force, so:

$$f = \mu N$$

Where μ is the proportionality constant and is called the coefficient of friction. The coefficient of friction depends on the nature of the two surfaces. Table 1 lists the coefficient of static friction and the coefficient of kinetic friction. For a given normal force, you can calculate the limiting or kinetic friction.

	μs	μk
wood on wood	0.5	0.3
steel on steel (smooth)	0.75	0.50
metal on metal (lubricated)	0.03	0.03
rubber on dry concrete	0.9	0.7
rubber on wet conrete	0.7	0.5
plastic on steel	0.2	0.2

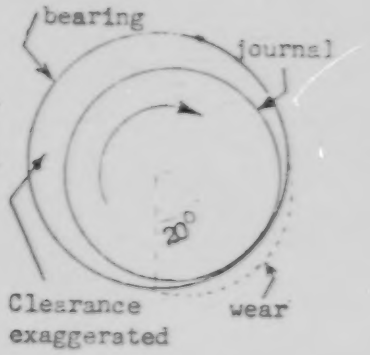
(Table 1)

EXAMPLE 1. A car weighing 4000 lb has a coefficient of limiting friction of 0.9 between tires and concrete. What is the maximum braking force that can be applied without skidding?

$f = \mu N = 0.9\ (4000\ \text{lb}) = 3600\ \text{lb}$

EXAMPLE 2. A steel shaft of a motor turns in a lubricated bronze bearing. The coefficient of kinetic friction is 0.12. A V-belt exerts a downward pull of 225 lb on the bearing. The bearing also supports 12 lb of an armature's weight. Find the frictional force and the retarding frictional torque on the 0.75 in shaft. Note that even though the forces are straight downward, the shaft tends to roll up the side of the bearing before slipping begins. Wear occurs in the dashed area, 20° from bottom dead center.

Fig 4



SOLUTION: The normal force is given by $N = F \cos \Theta$

$N = 237 \cos 20° = 223$ lb

The frictional force tangent to the journal is:

$f = \mu N = 0.12(223\ \text{lb}) = 26.8$ lb

The retarding torque is (Force x lever arm):

$T = f \cdot \ell = 26.8\ \text{lb} \times 0.375\ \text{in} = 10.0\ \text{in} \cdot \text{lb}$

ROLLING FRICTION

Use of wheels, rollers, or ball bearings greatly reduces friction since, theoretically, there is no sliding friction involved. In a practical sense, however, the wheel or the surface (or both) will

flatten some under the pressure of contact. A soft wheel tends to flatten on a hard surface (automobile tire for example). Consequently, a larger surface is in contact and some sliding is involved since there will be some relative motion.

A hard wheel on a soft track (wagon wheel rolling on a muddy road for example) leaves a deep track in its path. Not only is the wheel trying to roll uphill all the time trying to get up out of the track, but there is considerable sliding on the sidewalls of the wheel.

Steel rollers tend to flatten some and to sink into a steel track or raceway. Even though the effect would not be noticeable to the naked eye, nevertheless, it is present and some friction is present even in the best of ball or roller bearings.

Rolling friction is always less than sliding friction as a comparison of Table 1 and 2 shows. The formula for rolling friction is identical to that for sliding friction, but the coefficients of friction are different.

	μ
Rubber tire on concrete	0.04
Steel ball bearings on steel	0.0025
Steel roller bearings on steel	0.003

(Table 2)

ANGLE OF REPOSE

If the component of weight parallel to an incline is just equal to the frictional force, (see Fig. 5) then the object will just slide down the incline at constant speed. The net force along the incline is zero since P = f:

$W \sin \theta r = \mu W \cos \theta r$

therefore:

$\mu = \tan \theta r$

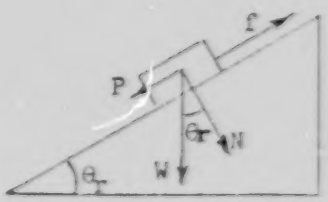


Fig 5

The coefficient of friction can be found by raising the incline until the object just slides downhill. The angle is called the angle of repose or the angle of uniform slip. As an example, kernels of grain or sand in a pile make a specific angle with the horizontal depending on the angle of repose or coefficient of friction between grains.

PART II

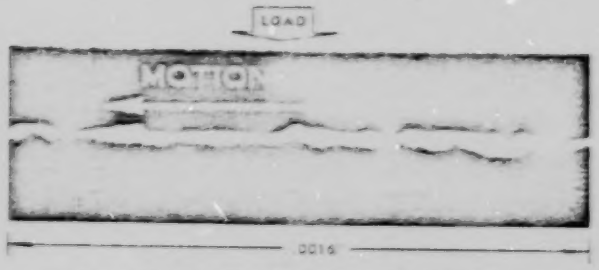
WHAT CAUSES FRICTION?

The forces that cause a tire to flex or flatten or those that are exerted on a wheel as it tries to roll up out of an indented raceway, have components in a backward direction. This backward component is a part of rolling friction. Another part of rolling friction, however, is attributed to sliding between surfaces in relative motion. The question, then, reduces to the cause of sliding friction.

If the surfaces are rough, the object is supported on stilts, peaks or prongs that hang down from it or stick up from the surface the object slides on. As the object begins to slide, the prongs bend over. After a high point has passed by, the prong then is released, perhaps vibrates a bit as it dissapates its stored up energy. It may permanently be bent or broken off. Friction can be attributed partially to the force required to bend these microscopic prongs.

A smooth surface has fewer prongs to bend and friction is reduced by smoothing the surfaces. A strange thing about friction, however, is that friction tends to increase after reaching a certain smoothness. Why does this happen? Before that question can be answered, some other discussion is necessary.

REAL CONTACT AREA



Magnified profile of highly polished surfaces shows how rough an apparently smooth metal surface can be and the small areas of actual contact between them. The finish of the two surfaces represented here is 8 microinches R.M.S. Magnification is 2000 times.

Figure 6 *

Figure 6 shows a highly magnified profile of very smooth surfaces. The four contact points have a real contact area that is a small fraction of the apparent area. The molecules of the upper surface are in real adhesive contact with those of the lower surface at these points. They are as close together at the four points of contact as they are inside the material of either object. Heat and electricity will conduct through these points (if the materials are good conductors). They are actually welded together at these points.

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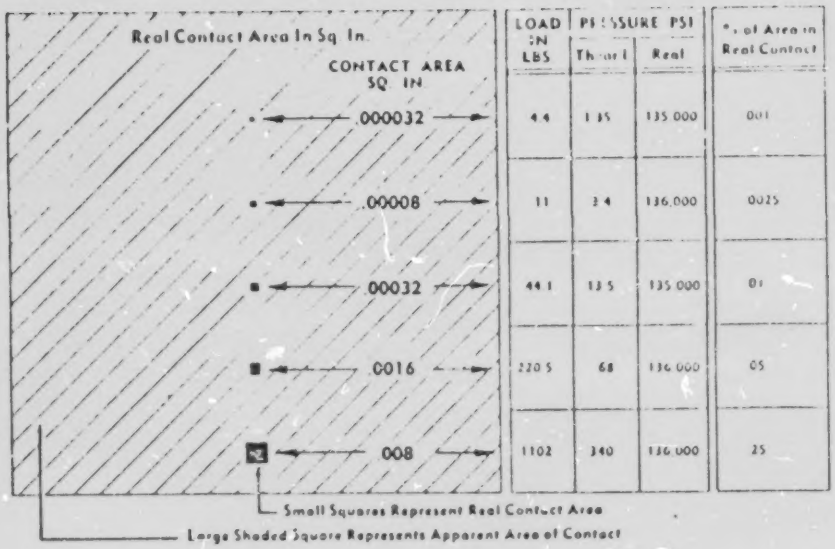

LOAD IN LBS	PRESSURE PSI		% of Area in Real Contact
	Theor'l	Real	
4.4	1.35	135,000	.001
11	3.4	136,000	.0025
44.1	13.5	135,000	.01
220.5	68	136,000	.05
1102	340	136,000	.25

Figure 7*

Electrical measurements of the actual contact area of two ground and lapped steel flats at various loads provides the data presented here. At each loading, true bearing pressure based on actual contact area is very high, approaching the compression yield strength of the material. It is surprisingly uniform despite the load imposed.

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The shaded portion of Figure 7 shows the apparent area of two steel flats in contact (1 in^2). The small dark squares show the real contact area as the normal force increases. The real contact area increases from 0.000032 in^2 to 0.008 in^2 as the normal force increases from 4.4 lb to 1102 lb. The percent of area in real contact increases from 0.001% to 0.25%.

Notice in Figure 7 that the apparent (theor'l) pressure (force divided by apparent area) increases from 1.35 lb/in^2 to 340 lb/in^2. The real pressure (force divided by real area) does not change and is very high, near the yield point of the metal.

Some quick calculations show that the real contact area increases in proportion to the normal force (see Fig. 7). Friction is, therefore, proportional to the real contact area even though it is unrelated to the apparent area. Real contact area is difficult to measure; electrical resistance is inversly proportional to area, so the contact area could be measured electrically if the materials are good conductors. Perhaps it's just as well that friction is determined as a function of the normal force.

Now to explain why friction increases as the surfaces become highly polished. When a smooth object slides over another, a force must break the adhesive (or cohesive) bonds at points of real contact. At rest, the object settles down and a few more points adhere. Once in motion, there is no time for settling. With fewer points in real contact at any instant, the coefficient of kinetic friction is less that that for static friction.

Surfaces with extreme smoothness have a greater ratio of real contact area to apparent area. There are more adhesive bonds to break as motion begins, so the frictional force becomes greater as surfaces become smoother. The real contact area may become a large percentage of the apparent area. In such cases, friction may be reduced by

reducing the apparent area. The bearing surface of jewelled bearings in watches is an example of such extreme smoothness.

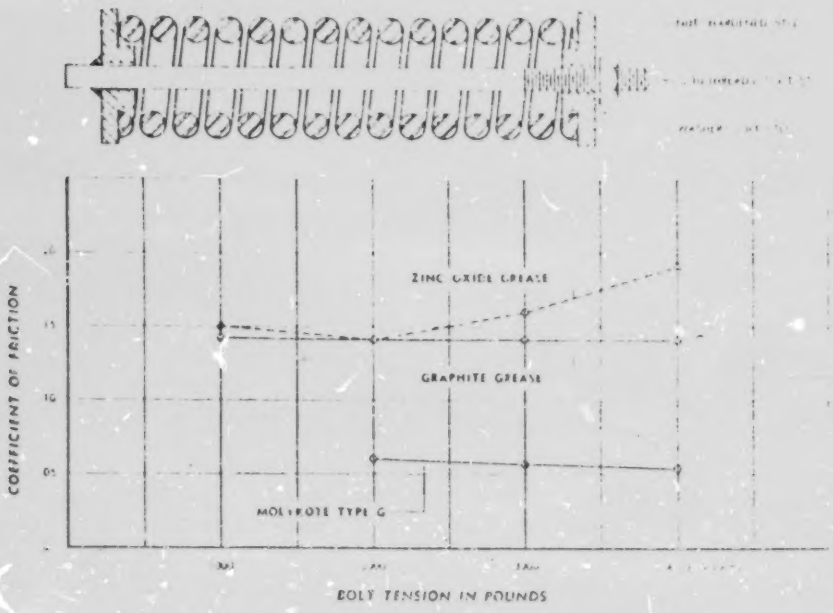

Figure 8*

Coefficient of friction for various solid lubricants calculated from data compiled with assembly shown above graph. A calibrated torque wrench was used and spring deflected to obtain bolt tension. Values for the molybdenum disulfide lubricant below 2000 lb tension were unobtainable because the wrench did not indicate the small torque values involved.

The coefficient of friction may change as higher pressure or higher temperatures are applied to the sliding surfaces. Figure 8 describes an experiment showing the change in the coefficient of friction as higher pressures are applied. The coefficient of friction of certain automobile tires such as "racing slicks" increases as the temperature goes up. The high sulfur content causes the tire surface to become sticky when heated. The nature of such changes is dependent on the nature of the materials themselves.

LUBRICATION

Fluid friction is a result of frictional force when a liquid flows past a solid surface and the flow between the molecules of the liquid itself. Since the molecules of a liquid are free to move, the use of liquids between sliding surfaces prevent most of the adhesion that is the source of friction. Fluid friction is much less pronounced than friction between solids (see Table 1). Naturally, there are great differences in lubricants.

Additional information and problem examples may be found in your text.

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PROBLEMS

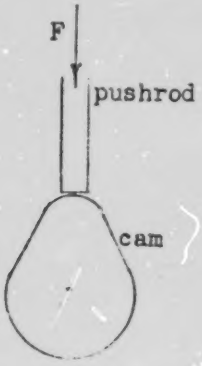
Module M 6 FRICTION

1. Explain the difference between real contact area and apparent area between sliding surfaces and the effect of each on friction.

2. Explain the difference among static friction, limiting friction, and kinetic friction between sliding surfaces.

3. What are the essential differences among sliding, rolling, and fluid friction?

4. A shop cart has large wheels which have a coefficient of friction of 0.06 including bearing friction. A 105 lb engine block rests at the center of the 75 lb cart. What force is required to move the cart? Is it necessary to calculate the friction on each wheel?

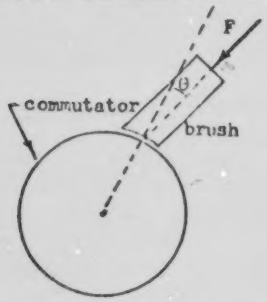
5. 

A camshaft in an engine has two cams per cylinder. The valve springs force the pushrod against the cam. The force is magnified by the lever action of the rocker arm. If the minimum force on the cam (valve closed) is 280 lb, and the maximum force (valve open) is 400 lb, find the minimum and maximum amount of friction on the cam. The coefficient of kinetic friction is 0.06.

6. A tow truck is pulling a farm truck with a load of grain on it. If the truck and load weigh 5 ton and the coefficient of rolling friction is 0.06, find the force of friction on the farm truck and the pull the tow truck must exert to maintain a low constant speed. Neglect air resistance.

7. In tightening a bolt, sliding occurs between the threads and between the head of the bolt and the washer. Correct tension, if it is required, is achieved with a torque wrench. If the tension in a ½ in bolt is 1000 lb, what is the friction (limiting) if the coefficient is 0.75? What happens to the tension and friction as the bolt is tightened?

8. A screw jack is used to lift a 1200 lb weight vertically. If the coefficient of limiting friction is 0.68, find the limiting frictional force between the threads of the screw. What is the kinetic friction if the kinetic coefficient is 0.48?

9. 

Metal graphite brushes on a starter motor commutator have a force of 1.00 lb radially (angle equals zero degrees). If the coefficient of friction is 0.07, what is the total frictional force exerted by <u>four</u> brushes?

PROBLEMS CONTINUED

10. The disk in a wheel brake is rigidly attached to the axle. Brake shoes press against each side of the disk. A frictional force of 425 lb on each wheel will prevent the car from creeping at a certain engine speed. Will a force of 490 lb on each shoe hold the car if the limiting coefficient of friction is 0.4?

11. The force on the crankshaft journal is a combination of inertial, centrifugal, and power forces. These combine or cancel during various parts of the four-stroke cycle. The power stroke exists during one of the four strokes, only. The greatest force on the journal is at the end of the exhaust stroke near top-dead-center and is downward. The least force is during the power stroke. If the greatest and the least forces on the journal of a certain engine at a certain speed are 3100 lb and 960 lb, find the greatest and the least frictional forces. The coefficient of friction is 0.03.

ANSWER KEYS (PROBLEMS)

Module M 6 FRICTION

1. See information sheet. Friction is independent of the apparent area.
2. Static friction varies from zero to the limiting friction, depending on the applied force. Kinetic friction is the average value after motion begins.
3. See information sheet
4. 10.8 lb, no
5. 16.8 lb, 24 lb
6. 600 lb
7. 750 lb, both increase
8. 816 lb, 576 lb
9. 0.28 lb
10. No, friction is 196 lb on each shoe, 392 lb on each wheel.
11. 93 lb, 28.8 lb

EXPERIMENTS (T)

Module M 6 FRICTION

PURPOSE: The purpose of this experiment is to study friction and some of the factors that influence friction.

CAUTIONS:

1. Read all the instructions before handling any of the equipment.
2. Keep the plastic foam keeper in place on the Harvard trip balance when it is not being used.
3. The balance scale is a delicate instrument. When you weigh the wooden block, take it to the balance scale instead of carrying the balance scale to your lab station. It recieves less wear and tear this way.
4. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
5. Observe all cautions listed in the procedure section below.

EQUIPMENT: Check to see if all the following equipment is available before you start. Ask your instructor if you have any questions about the equipment.

1. Incline Plane (Sargent-Welch #0809)
2. Friction Block (2) (Sargent-Welch #0977)
3. String
4. Weight hanger
5. Slotted weight set
6. Balance scale and weights available in classroom.

INFORMATION: Friction always opposes motion or the tendency of motion. On an incline, friction is a force downward when an object is being pulled up the incline. When the object moves down the incline, friction is upward along the incline.

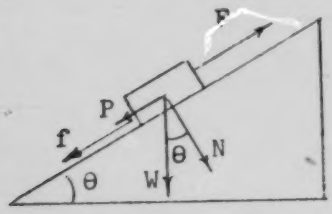


Fig 1

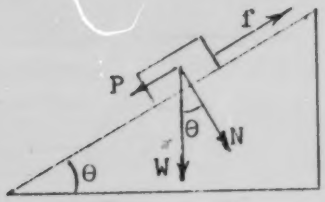


Fig 2

Figure 1 shows the first case where a force (F) pulls the object upward. It must overcome the effects of force P (component of the weight down the incline, $P = W \sin \theta$) and friction (f). Figure 2 shown an object moving down the incline. Notice that friction is upward in this case. The object will move only if P is larger than f.

The frictional force (f) is equal to the normal force (N) (the perpendicular component of the weight) times the coefficient of friction (μ).

$$f = \mu N$$

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When an object slides on a horizontal surface, the normal force is just the weight of the object.

For further information, see your text or the information sheet in this booklet.

PROCEDURE:

1. Place the inclined plane (set on 0°) on a table or lab bench so the pulley hangs over the edge.

NOTE: Exact leveling of the surface is unnecessary.

2. Weigh the friction block on the balance scale. Record on the data sheet.

3. Attach the wooden friction block to one end of the string on the hook provided and attach the other end of the string to the weight hanger.

4. Place the block on the surface of the incline plane near the center and let the weight hanger hang over the edge of the table with the string in the pulley.

NOTE: The string between the friction block and the pulley should be parallel to the plane. Adjust by raising or lowering the pulley.

5. Hang slotted weights on the hanger to find the force required to just move the friction block along the plane. Be sure to include the weight of the hanger (50 g). The weight on the hanger and the hanger itself is equal to the frictional force on the block. Record on the data sheet.

NOTE: The block should just creep when you tap the incline plane surface <u>lightly</u> with your fingernail or pencil.

6. Add 200 g to the weight of the block by laying slotted weights on top.

7. Repeat step 5 after resetting the block in the same place on the incline. The block should creep at about the same rate with the same amount of tapping. Record the data.

8. Repeat steps 6 and 7 with 400 g, 600 g, and 800 g on the block. Record the data.

9. Calculate the coefficient of friction for each line, record in the proper place and find the average.

10. Lay the block on edge, adjust string so it is parallel to the plane. Measure the force of friction by hanging slotted weights on the hanger.

11. Compare the frictional force measured on edge to that measured in step 5 by calculating the percentage ratio.

12. The results of steps 5 and 6 should show that friction is independent of the apparent area even though friction may be slightly different. What do you attribute the difference to?

13. Repeat steps 1 through 9 for the second friction block.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 8

Title: ENERGY & POWER

Module Contents:
1. Work, energy, and power
2. Classification of energy
3. Units of work, energy, and power
4. Energy transformation and the work equation
5. The law of conservation of energy

Program: This module has been prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to study the principles of work and energy. Interactions of objects have previously been studied in terms of forces and acceleration which are vector quantities. The same interactions can be studied more easily, however, with the use of the scalars: work, energy and power. The law of conservation of energy unifies and simplifies the description of motion. Practical examples are included. This module is a prerequisite for modules on simple machines, power measurement, and others.

Producer: Gene Waring

Date Produced: October, 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTION

Module M 8 ENERGY & POWER

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define work, energy, and power.
2. State the derived units of work, energy, and power in the MKS, cgs, and British systems and convert one to the other.
3. Define kinetic energy, elastic potential energy and gravitational potential energy.
4. State the formulas for kinetic elastic potential and gravitatational potential energy, for work, for power and for Hooke's law for springs.
5. Solve various problems in which the formulas in objective 4 are involved.
6. Cite several examples of one form of energy in the process of being transformed to other forms.
7. State the law of conservation of energy and the work equation, and solve various problems involving these principles.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of energy and power. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4).

(OVER)

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read Chapter 4, sections 4.1-4.6, pages 84-94, and section 4.11, pages 103-106, and Chapter 10, section 10.5, pages 247-248.

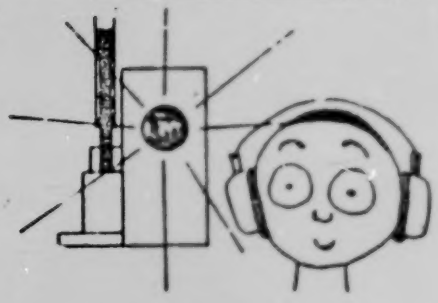
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read part of Chapter 7, sections 7.1 to 7.7, pages 77-85 (omit section 7.8, 7.9, and 7.10).

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of Chapter 9, sections 9.1-9.3, pages 103-116.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 8, pages 91-107 (you may omit page 97).

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read Chapter 9, pages 123-141 (omit section 9-4).

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 70) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Gravitational Potential Energy, (BFA Ealing 80-3817)

B. Kinetic Energy, (BFA Ealing 80-3825)

C. Conservation of Energy-Pole Vault, (BFA Ealing 80-3833)

D. Conservation of Energy-Aircraft Takeoff, (BFA Ealing 80-3841)

E. Conservation of Energy, (BFA Ealing 80-276)

F. A Method of Measuring Energy-Nails Driven into Wood, (BFA Ealing 80-3791)

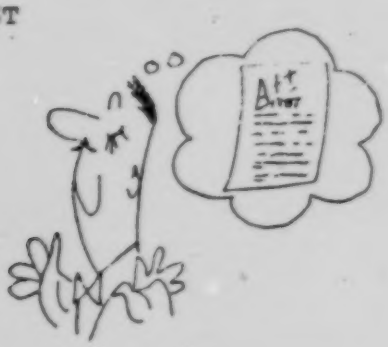
III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving work and energy problems. The problems from number six on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about work, energy and power.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M-8) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST



You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST (T)

Module M 8 ENERGY & POWER

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Work will always be done on an object if an external force acts on it.

T - F 2. A pair of automobiles of equal mass and equal speed, but going in opposite directions have a net kinetic energy of zero.

T - F 3. One joule equals one newton-meter.

T - F 4. In lifting a TV set from the floor to a table, the work done is: the weight of the set times the height of the table.

T - F 5. Energy can be created only in machinery classified as engines, motors, generators and furnaces.

6. The unit of energy expressed in MKS units is:

a) newton
b) ft·lb
c) joule
d) dyne

7. A 64 lb weight is lifted 20 ft. The work done is:

a) 1280 J
b) 41 000 ft·lb
c) 12 800 erg
d) 1280 ft·lb

8. A 4000 lb automobile is traveling 45 mi/h (66 ft/s). What is its kinetic energy?

a) 272 000 ft·lb
b) 272 ft·lb
c) 272 000 watts
d) 8 710 000 ft·lb

9. A spring has a force constant of 3.6 lb/ft. A force of 5 oz will stretch it:

a) 0.087 in
b) 1.04 in
c) 1.39 ft
d) 0.72 ft

(OVER)

10. What average force would be acting on a 25 g bullet as it penetrates wood to a depth of 15 cm? Its speed just before impact is 260 m/s.

11. An elevator and its contents weigh 3 ton. It moves 300 ft to the top of a mine shaft in 50 s. What power is required?

ANSWER KEY TO THE SELF-EVALUATION TEST (T)

Module M 8 ENERGY & POWER

Question-Answer		If you missed this question, you are directed to these learning activities:
1.	F	I. Reading
2.	F	I. Reading
3.	T	I. Reading
4.	T	I. Reading
5.	F	I. Reading
6.	c	I. Reading, or III. Solving Problems
7.	d	III. Solving Problems, II. Listening/Viewing, or V. Experiment
8.	a	III. Solving Problems, II. Listening/Viewing, or V. Experiment
9.	b	III. Solving Problems, II. Listening/Viewing, or V. Experiment
10.	5630 N	III. Solving Problems, or II. Listening/Viewing
11.	65.6 hp	III. Solving Problems

INFORMATION SHEET

Module M 8 ENERGY & POWER

WORK

Inertia is the property of matter by which an object resists changes in its motion. An object in a friction free environment requires no forces to keep moving or to keep from moving. Objects that cannot readily be moved such as those with large inertia, or those that are bolted, rooted or cemented down, require extremely large forces to cause movement.

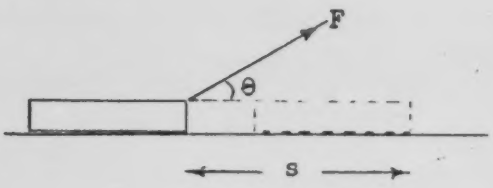
No changes are occuring in the case of objects moving without external forces or in the case of objects with external forces but no movement. Nothing is being accomplished. No work is being done. In both cases either force or movement is lacking.

Work is defined as the product of the force and the distance moved:

$$W_k = Fs$$

More exactly; work in the product of the component of the force in the direction of motion and the distance moved, or:

$$W_k = Fs \cos \theta$$



Where θ is the angle between the direction of the force and the direction of motion.

In the two cases cited above, either F or s is zero, so no work is done.

A third case in which no work is done is when the cos θ is zero. This happens when θ is 90°, when the direction of F is perpendicular to the direction of s (uniform circular motion).

Work is done on an object, however, when none of the three quantities (F, s, and cos θ) is zero. A second object must be involved in order to exert the force according to Newton's third law (action-reaction). In order for the second object to exert the force and cause movement or, in other words, to do work on the first object, it must possess an ability or a capacity to do work. It must possess energy.

ENERGY

Energy is the ability of an object to do work. The object has the energy stored within it. Energy can be stored in one of several different forms:

1. Chemical: gasoline, coal, electrolytes, food, animals

2. Electical potential: electric or magnetic fields

3. Gravitational potential: snow in the mountains, or water behind dams

4. Kinetic: flywheels, wind, ocean streams, tides, moving objects

5. Elastic potential: springs, torsion bars

6. Heat: heat bins, steam, hot water heaters

7. Nuclear: Uranium, Plutonium, Hydrogen

The energy in most of these forms can be bought or sold by individuals, by large corporations, or by power companies. We buy gasoline and batteries to operate our car, and food to keep out bodies operating. When we employ someone for physical labor, we buy the chemical energy stored in their bodies.

Power companies buy coal, natural gas, propane, or diesel fuel to operate their generators and resell the energy in a different form.

Energy can be transported by several methods:

1. Conduction. This is the movement of energy through a material without actual transfer of the material. Heat, sound, and electrical energy are easily transported this way. Current in power lines is one example where large amounts of energy are transported by conduction.

2. Natural convection. This is the movement of the material that contains the energy. Hot air rises, water flows downhill in open streams. Ocean currents, and air currents are other examples of natural convection of energy.

3. Forced convection. This is the movement of the material that contains the energy when the movement is forced. Trains move coal, pipelines move natural gas, trucks move gasoline, pumps move water uphill, and fans move air. These are examples of forced convection.

4. Radiation. This is the movement of the energy through space without the aid of any material. Radio waves move from transmitter to receiver for example. Naturally, the energy is emitted by one object and will eventually be absorbed by another object, but matter always slows down or hinders the process when the transfer is by radiation. Energy transferred this way is in a form of electromagnetic radiation such as: radio waves, light, x-rays, and a number of others.

Energy can be stored by storing the material that contains the energy. We transfer energy usually by transferring the material. We do all these things with energy (buy, sell, move, and store it) without ever really knowing what it is. A mountain of coal or huge tanks of oil are quite obvious, but the energy they contain is not. It is only when the energy is being transformed or dissapated (used) that its presence becomes known or felt.

Individuals seldom see energy being gobbled up very rapidly. We wind a watch and see the energy stored in the spring being "used" very slowly. We see electric motors driving a fan. Modern automobiles and roads allow us to move so smoothly we are unaware of the energy involved except when a collision occurs.

We may shy away when we feel the ground shaking as a huge freight train moves by at 70 mi/h. We may be a bit nervous from the vibrations we feel down in the turbine room of a large hydroelectric plant. At 50 yards, we may have to turn our face away from the heat emitted from a red hot pig of iron in a steel factory. Volcanoes, tornadoes, and floods as well as nuclear bombs make us feel very puny indeed.

Since we can buy, sell, transport, and store energy in the material that contains the energy, we have a definite feeling for it. Its almost as though we should be able to pick up a handful of energy without picking up the material along with it. But, of course, we can't. We can do one more thing with it, though, we can "use" it. We can buy, sell, move, store, and "use" it. You need to be sure that you know what the expression "using energy" means.

THE LAW OF CONSERVATION OF ENERGY

When we use a tank of gasoline, the gasoline is gone forever. Is the energy that the gasoline contained also gone forever? No, the energy was just transformed from chemical energy to other forms. Most of it was converted to heat. Some went out the exhaust. Some went with the air blowing through the radiator. Some was converted to heat as the automobile overcame road and air friction. Some was given off as sound. Some was converted to kinetic energy of the car, but, when the brakes were applied, even that was transformed to heat in the brake drums.

The energy in the gasoline was highly concentrated, but after it is used, it is distributed very widely in the atmosphere over a range of one or two hundred miles. Some of the energy may have been absorbed by the atmosphere to warm it ever so slightly. Some probably radiated to outer space. The energy in the tank has been used. It still exists but it is now in an unusable form. We cannot reuse it. It was not destroyed but we could never concentrate it as much as it was originally in the gasoline tank.

The energy was not destroyed; it cannot be destroyed. Energy cannot be created either. That is a law of nature: The law of conservation of energy.

> "Energy can be transformed from one form to another, but it cannot be created or destroyed."

Remember that energy is the ability to do work. How can work be done during the process when energy is being transformed from one form to another?

A few examples illustrate the answer. Chemical energy stored in gasoline is converted to heat during combustion. Gases expand when heated, perhaps in the cylinder of an engine, creating a force on the piston and making it move. The combination of force and movement indicates work being done. Dynamite moves rocks and trees in a similar way.

Gravitational potential energy of water behind a dam is converted to kinetic energy as it flows downhill. The gravitational force causes the water to move. Work is done on the water. Any moving object can do work. It can collide with other objects, exerting forces and causing motion. The moving water may be directed towards the blades of a turbine, exerting forces and causing rotary motion which can be used in many ways. Gravity also causes air to rise when it is heated. Moving air can cause rotary motion (windmills) the same way moving water does.

Kinetic energy of the rotating turbine is converted to electrical energy. Chemical energy in a battery or nuclear energy, can also be converted to electrical energy. Electrical energy may be the kinetic energy of electrons moving in a conductor, or in its pure form, may be stored in electric or magnetic fields. Whenever an electric current passes through a magnetic field, the wire conducting the current if forced to move. Thus, the magnetic fields cause rotary motion of the armature of a motor. Work is done by the magnetic field on the wires during the energy transformation.

Work is done by frictional forces when a car is stopped by pressing the brake. Kinetic energy is transformed to heat in the process.

KINETIC ENERGY

Mechanical energy is kinetic, gravitation potential, and elastic energy. Changes in any of these involves a mechanical change in speed, position, or state of strain.

Kinetic energy is energy an object has when it is moving. The formula for kinetic energy is:

$$E_k = \tfrac{1}{2}mv^2$$

Where v is the object's velocity, and m is its mass.

Keep in mind that mass is weight divided by the acceleration of gravity ($m = w/g$) and must be calculated when using the British measuring system or substituted to get the formula:

$$E_k = \frac{wv^2}{2g}$$

Use the first equation with metric units and the second with British.

Example: How much kinetic energy does a 4000 lb automobile have when going 55 mi/h?

Given: $w = 4000$ lb
$g = 32$ ft/s^2
$v = 55$ mi/h $= 80.67$ ft/s

$$E_k = \frac{wv^2}{2g} = \frac{4000 \text{ lb} \times (80.67 \text{ ft/s})^2}{2 \times 32 \text{ ft/s}^2}$$

$$E_k = 407\,000 \text{ ft·lb}$$

Notice that the units are the same as the units for work.

GRAVITATIONAL ENERGY

Gravitational potential energy is energy an object has due to its position. It is given by the formula:

$$E_G = mgh$$

where h is the vertical height from the zero reference level. The zero reference level may be chosen (by you) to be any horizontal plane near the object. For Brisish units use the formula:

$$E_G = wh$$

Example: A table, 1 m high, rests on the second floor 5 m above the ground. A 5 kg object is held 2 m above the table. Find its gravitational potential energy relative to the table top, floor, and ground level.

Given: $h = 2$ m relative to the table top

$h = 3$ m relative to the floor

$h = 8$ m relative to the ground

$$m = 5 \text{ kg}$$

$$g = 9.8 \text{ m/s}^2$$

$$E_G = mgh = (5 \text{ kg})(9.8 \text{ m/s}^2)(2 \text{ m}) = 98 \text{ J (table)}$$

$$E_G = mgh = (5 \text{ kg})(9.8 \text{ m/s}^2(3 \text{ m}) = 147 \text{ J (floor)}$$

$$E_G = mgh = (5 \text{ kg})(9.8 \text{ m/s}^2(8 \text{ m}) = 392 \text{ J (ground)}$$

Again notice the units are the same as the units of work. An object positioned below the zero reference level is said to have negative gravitational energy. Work would have to be done on it to move it to the zero level, whereas an object with positive energy can do work when it arrives at the zero level, since it would now possess kinetic energy.

ELASTIC ENERGY

When a spring is stretched the change in length is proportional to the stretching force, usually expressed as:

$$F = ky$$

Where k is called ths spring constant of the spring, and y is the increase in length due to the stretching force F. The spring constant tells you how much force is required to stretch a spring unit length. It normally has units of lb/ft, N/m, etc. It is a large number for stiff springs and a small number for weak springs.

Example: How far will a spring stretch if 5 lb is applied to it? 3 lb will stretch it 0.12 ft.

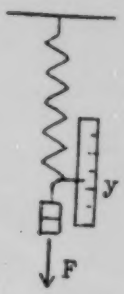
Given: $F = 5 \text{ lb}$

$F_i = 3 \text{ lb}$

$y_i = 0.12 \text{ ft}$

$k = F_i/y_i = 3 \text{ lb}/0.12 \text{ ft} = 25 \text{ lb/ft}.$

$y = F/k = 5 \text{ lb}/(25 \text{ lb/ft}) = 0.2 \text{ ft}.$



The energy (elastic) in a stretched spring is equal to the work done in stretching the spring. Since the amount of stretch is proportional to the stretching force, you must use the average force (Fav = F/2) in calculating the work done. The elastic energy stored in a spring is given by the formula:

$$Ee \quad \tfrac{1}{2}\, ky^2$$

Example: Find the energy stored in the spring of the previous example when 5 lb is applied to it.

Given: $k = 25$ lb/ft

$y = 0.2$ ft

$$Ee = \tfrac{1}{2}\, ky^2 = \tfrac{1}{2}\,(25 \text{ lb/ft})(0.2 \text{ ft})^2$$

$$= 0.5 \text{ ft·lb}$$

$$Wk = \tfrac{1}{2}\, Fs = \tfrac{1}{2}\,(5 \text{ lb})(0.2 \text{ ft}) = 0.5 \text{ ft·lb}$$

POWER

Power is the rate at which work is done or the rate at which energy is transformed.

$$P = Wk/t$$

Example: How much work can a 0.5 kW motor do in 1 h?

Given: $P = 500$ W $= 500$ kg m^2/s^3

$t = 3600$ s

$$Wk = Pt = (500 \text{ kg m}^2/\text{s}^3)(3600 \text{ s}) = 1\,800\,000 \text{ J}$$

Unit conversion factors between watts, kilowatts, horsepower, ft lb/s, and ft lb/min, can be found in your text.

When work is being done against a constant load so that motion remains constant, power is given by the formula:

$$P = Fv$$

An automobile going at constant speed on level ground would be an example of this.

Example: Find the horsepower developed by a truck to maintain 45 mi/h if the force of friction is 300 lb.

$v = 45$ mi/h $= 66$ ft/s

$F = 300$ lb

$$P = Fv = \frac{(300\ lb)(66\ ft/s)}{(550\ hp/ft \cdot lb/s)} = 36\ hp$$

EFFICIENCY

The efficiency of a machine or device that transfers or transforms energy, is the ratio of output work or power to the input work or power and is usually expressed as a percentage.

THE WORK EQUATION

If energy is transformed so that forces are applied to an object, its velocity, position or state of strain will change. The original energy in any form is transformed to kinetic, gravitational potential, elastic, or some combination of these three. Usually elastic energy doesn't change unless stretching, bending, twisting, etc. take place as in a collision. In the following discussion, it is assumed that no springs, torsion bars, etc. are involved.

If there is a net change in the kinetic and gravitational potential energy that an object possesses, either the object gave up energy, or it absorbed energy from some other object. If an automobile's speed increases on a level road as an example, the increase in its kinetic energy must have come from the chemical energy in the gasoline. A force was applied to the automobile by the road and it acted through the distance covered while the accelerator pedal was down. The work done on the car is just equal to the change in kinetic energy:

$$\tfrac{1}{2} mv^2 - \tfrac{1}{2} mv_0^2 = Fs$$

Either side of the equation gives the amount of chemical energy used to accelerate the car and does not include the energy used to overcome friction and lost in the form of heat or sound.

Example: A car on the level road accelerates from 30 mi/h in distance of 300 ft. What is the average accelerating force on the car if its weight is 4000 lb?

Given: $m = w/g = 4000\ lb/32\ ft/s^2 = 125\ slug$

$v = 45\ mi/h = 66\ ft/s$

$v_o = 30\ mi/h = 44\ ft/s$

$s = 300\ ft$

$\frac{1}{2}$ (125 slug)(66 ft/s)^2 - $\frac{1}{2}$ (125 slug)(44 ft/s)^2 = F·(300 ft)

F = 504 lb

If the speed of the car had decreased from 45 mi/h to 30 mi/h in the same distance, the average braking force would have been 504 lb, also.

If motion up or down a hill is included, the work equation becomes:

$$(\tfrac{1}{2} mv^2 - \tfrac{1}{2} mv_0^2) + (mgh - mgh_0) = Fs$$

The first parenthesis contains the change in kinetic energy; the second contains the change in gravitational potential energy. If the zero reference level is chosen at the low point, then either h or h_0 equals zero, so the equation is simplified by one term.

In some situations where the external force is negligibly small, then the right side of the equation becomes zero. In that case, the change in kinetic energy equals the negative of the change in gravitational potential energy. An increase in one equals the decrease in the other.

Example: A pendulum swings out and upward a vertical distance of 4 cm. What is its speed as it passes through the low point of the swing?

Take the low point as the zero reference level,

Given:

$h = 0$

$h_0 = 4$ cm

$v_0 = 0$

$g = 980$ cm/s^2

Notice the mass is not given. However, since mass is in every term, it will drop out of the equation. The second and third term on the left and the term on the right drop out because they have a zero factor. So, the equation becomes:

$\frac{1}{2} v^2 - gh = 0$

$\frac{1}{2} (v^2) - (980 \text{ cm/s}^2)(4 \text{ cm}) = 0$

$v = 88.5$ cm/s

The force on the right side of the work equation is constant if the velocity doesn't change as when a car is on a hill with the engine or brakes maintaining a constant speed. Changes in speed mean changes in air resistance. If the change in air resistance is negligible, then Newton's second law of motion (module M 7) applies. Distance and time can then be calculated using kinematics (module M 5).

Example: A car coasts up a straight incline (I-80, Milford, west bound exit). It leaves the interstate (bottom of incline) at a speed of 45 mi/h. With the transmission in neutral, it coasts, reaching the top in 18.5 s, and still going 26 mi/h with space enough to stop at the stop sign. In order to measure the frictional force, the time for the car to coast through the same speed range on level ground was measured and found to be 29.5 s. Find the vertical height of the incline.

Given:

$v_0 = 45$ mi/h = 66 ft/s

$v = 26$ mi/h = 36.8 ft/s

$t_x = 18.5$ s (on exit)

$t_\ell = 29.5$ s (on level)

$h_0 = 0$

Note: $F = ma = m\,\frac{(v - v_0)}{t_\ell}$ assuming force is nearly constant, and $s = \frac{(v - v_0)}{2}\,t_x$

so, the work equation becomes:

$$(\tfrac{1}{2}\,mv^2 - \tfrac{1}{2}\,mv_0^2) + (mgh - mgh_0) = m\,\frac{(v - v_0)}{t_\ell}\,\frac{(v + v_0)}{2}\,t_x$$

Note: m drops out and so does the term with h_0 so:

$$\tfrac{1}{2}\,(v^2 - v_0^2) + gh = \tfrac{1}{2}\,(v^2 - v_0^2)\,\frac{t_x}{t_\ell}$$

$$h = \frac{(v^2 - v_0^2)}{2g}\left(1 - \frac{t_x}{t_\ell}\right)$$

$$h = 16.9 \text{ ft}$$

This example was performed as an experiment at Milford and subsequent measurement of the vertical height with surveying equipment gave a value of 17.06 ft for comparison.

PROBLEMS (T)

Module M 8 ENERGY & POWER

1. Does a man sitting still in a moving automobile possess kinetic energy? Explain.

2. A 5 kg mass is held 2 m above a 1 m table. One person says the mass has 98 J of gravitational potential energy and another says it has 147 J. Who is correct? Explain.

3. A bullet in a gun fires. The bullet, after traveling 100 yd, is imbedded in a sand bag. What was the original form of energy? What forms does it take while the bullet is moving? After being imbedded in the sand bag?

4. One car is at the top of a hill, the other only half way up. How does the gravitational energy relative to the bottom of the hill compare if they have the same weight? If one was moving at twice the speed as the other on level ground, how does their kinetic energies compare?

5. Are work, energy, and power vectors or scalar quantities?

6. Two springs have different spring constants. If they have equal lengths and are stretched by the same force, is more work done on the spring with the larger constant? Is more work done on the one with the larger constant if they are both stretched through the same distance?

7. What are the units of work, energy, and power in each of the cgs, MKS, and British measuring systems? Express each of these in fundamental units for each system.

8. A 175 lb engine is lifted 3.5 ft when being removed from an automobile by a hoist. How much work is done on the engine?

9. A 4000 lb automobile is lifted 5.5 ft on a hydraulic lift. If the hydraulic piston and its arms weigh 750 lb, what is the increase in gravitational potential energy? How much work is done by the hydraulic lift? What is the force exerted on the bottom of the piston by the fluid?

10. A tow truck has 500 lb of air resistance and road friction at 55 mi/h. How much power must the engine develop to maintain this speed? (55 mi/h = 80.7 ft/s)

11. A diesel tractor develops 82 hp when pulling a 5-bottom plow at a constant speed of 5 mi/h. What is the draw-bar pull? A model 1466 turbo International (diesel) tractor has a maximum power take off rating of 146 hp (University of Nebraska tractor testing Information) and a draw-bar rating of 127 hp. Find the maximum draw-bar pull the tractor can exert. Find the efficiency of the drive train.

INFORMATION NOTES:

Of the total energy in a gallon of gasoline (89 000 000 ft·lb), only a small amount is available for propelling the automobile. About 35% is removed by the coolant, and is dumped into the atmosphere in the form of heat by the radiator-fan cooling system. Another 35% is also dumped into the atmosphere in the form of heat through the exhaust system. Of the 30% remaining for doing work, about 5% is used to overcome friction within the engine: between rings and cylinder, in bearings, etc.

Approximately 10% of the energy available must overcome the power-train friction (transmission, differential, wheel bearings, etc.) Other energy is need to operate the valve springs, pull air into the cylinders, push air out of the cylinders, drive the water pump and fan. Other minor requirements involve the energy used to drive the fuel pump, oil pump, ignition, distributor rotor, and speedometer cable. Accessories that use energy include the lights, radio, CB radio, tape deck, horn, heater fan, cigarette lighter, and wiper motor. The alternator that supplies energy to such equipment is driven by V-belts directly off the engine shaft. The alternator is about 80% efficient. (A generator is about 65% efficient.) Air conditioners and power steering pumps are large users of energy coming directly off the shaft. In addition, energy is necessary to do the flexing of the V-belts that drive this equipment. Flexing of the tires, also requires energy.

Diesel fuel has approximately the same amount of energy in it per gallon as does gasoline (87 000 000 ft lb for diesel fuel). A diesel engine, however, is more efficient. Instead of losing 70% of the energy (exhaust and cooling systems) it loses about 65%.

The following problems are designed to help you study work, energy and power and at the same time to gain some insight into the working of internal combustion engines.

12. A certain automobile gets 15 mpg at a speed of 60 mi/h. (One gallon is used every 15 min). If each gallon contains 89 000 000 ft lb of energy, what rate does this automobile use energy in horsepower?

13. On the road, an automobile must overcome road friction and air resistance. If the absolute top speed of a car is 105 mi/h on level road (no wind), it is using energy at the fastest rate possible. Find this maximum input power in horsepower from the gasoline if the car is getting 6 mpg. (One gallon is used every 3.43 min). See problem 12.

14. If 15% of the input power of the automobile in problem 12 is used to propel the car on a level road with no wind, find the combination force of friction and air resistance. Its speed is 60 mi/h.

15. The engine in the automobile in problem 12 is turning at 3000 rpm. It is a V-8 engine. Each of the valves travel 0.45 in between open and closed position. The springs compress 7/16 in when 110 lb is applied. Find the spring constant and the energy stored in one spring when compressed (valve open). Find the work done in compressing the sixteen springs in 1 min. If 25% of the energy is recovered, ie: transmitted back to the crankshaft through the cams. What power in horsepower is required to operate the valve springs at this speed? NOTE: This does not include the work done against friction in the valve train.

16. Restrictions in the cooling system of an engine (radiator, hoses, thermostats and cooling jackets) create a lot of resistance to the flow of the coolant. At 3000 rpm, the two pumps on the engine in the previous problems have to pump the coolant against a friction head of 115 ft. (The work done equals the increase in gravitational potential energy that the coolant would have if it were lifted to a height of 115 ft). If the pumps move the coolant at 66 gal/min, how much work is done in 1 min? (Each gallon weighs 8.8 lb). What is the horsepower output of the pumps at that engine speed? If the pumps are 85% efficient, what horsepower is drawn from the engine? What power is required at an engine speed of 5000 rpm if the flow rate is 100 gal/min and the friction head is 355 ft?

17. The fan on the previous automobile moves air at a speed of 30 ft/s. The air, having passed through the radiator, is warm and less dense than normal. Assume 4.5 lb of air is moved each second. Find the kinetic energy of the air that passes through the fan in 1 s. What is the output power in horsepower of the fan? If the output of the fan is 70% of the input, find the power the fan draws from the engine.

18. The pressure in the cylinder of an engine during the intake stroke is less than atmospheric pressure. Although it varies throughout the stroke, it averages about 2.4 lb/in^2 vacuum, depending on engine speed. This amounts to an average upward force of 33 lb on the downward moving piston. If the stroke is 3.64 in, how much work is done on the piston during the intake stroke? If this engine is the same as in the previous problems (V-8 turning at 3000 rpm), find the work done in 1 min. NOTE: This is the work required to move the air-fuel through the carburetor and manifold. What power is required for this work?

NOTES: The power losses during the intake and exhaust stroke are called pumping losses. The loss during exhaust is less for the following reasons: the exhaust valve opens before the compression stroke is over. The hot compressed gases suddenly and rapidly move out the exhaust port. The inertia of the gas carries it beyond normal pressures and actually creates a slight

vacuum in the cylinder. This is similar to a mass on a spring or a pendulum swinging past the equilibrium point before returning. By the time the vacuum has been created, the piston is past bottom dead center and into the exhaust portion of the cycle. The piston then moves rapidly upward, slightly compressing the remaining gases as they are driven out the exhaust. Near the end of the exhaust stroke, the intake valve opens, creating a vacuum at the end of the stroke, also. Thus, the average pressure is lower because of the vacuum at each end of the stroke.

19. The average pressure during the exhaust stroke is 1.3 lb/in^2 and creates an average downward force of 17.9 lb on the upward moving piston. How much work is done on the piston during the 3.64 in movement during the exhaust stroke? How much work is done in 1 min (V-8, 3000 rpm)? What power is required?

20. The driver of the previous car is traveling on a level road on a chilly, rainy, windless autum night. The ignition requires 30 W of power, four headlamps require 50 W each, four taillights require 6 W each, the windshield wiper motor requires 70 W, the radio requires 10 W and the heater motor requires 50 W. What total power in horsepower is required as output from the alternator? If the alternator is 80% efficient, what horsepower must be provided by the engine?

ANSWER KEY (PROBLEMS) (T)

Module M 8 ENERGY & POWER

1. Yes, relative to ground.

2. Both,98 J-zero reference is table, 147 J-zero reference is floor.

3. Chemical, kinetic, heat

4. 2:1, 4:1

5. Scalars

6. No (less), yes

7. erg, erg, erg/s — g cm^2/s^2, g cm^2/s^3
J, J, W — kg m^2/s^2, kg m^2/s^3
ft·lb, ft·lb, ft·lb/s — ft·lb, ft·lb/s

8. 612 ft lb

9. 26 100 ft·lb, 26 100 ft·lb, 4750 lb

10. 73 hp

11. 6150 lb, 9530 lb, 87%

12. 180 hp

13. 786 hp

14. 169 lb

15. 3020 lb/ft, 2.12 ft·lb, 50 900 ft lb, 1.16 hp

16. 66 800 ft lb, 2.02 hp, 2.38 hp, 9.47 hp

17. 63 ft lb, 0.12 hp, 0.16 hp

18. 10.0 ft lb, 120 000 ft lb, 3.64 hp

19. 5.43 ft lb, 65 200 ft lb, 1.97 hp

20. 0.51 hp, 0.64 hp

EXPERIMENTS

Module M 8 ENERGY & POWER

PURPOSE: The purpose of this experiment is to study Hooke's law as it applies to springs and to study the work done on and the energy stored in a spring when it is stretched or compressed.

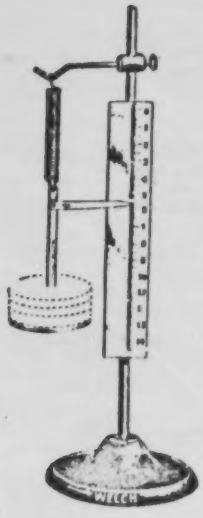
CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the prodedure section of these instructions.

EQUIPMENT: Check to see if all the following equipment is available before you start.

1. Welch #569 Hooke's Law Apparatus
   A. Stand with mirror scale
   B. Weight hanger with pointer
2. Two spiral springs (one large, one small)
3. One set of slotted weights

PROCEDURE:



By permission: Sargent-Welsh Scientific Co., Instructions for Hooke's Law Apparatus

1. Set up the apparatus as shown in the diagram, supporting the large spiral spring vertically. The pointer should now be horizontal in front of the scale.

NOTE: The pointer is a part of the weight hanger. The scale has a mirror finish so you can eliminate parallax errors by reading the scale when the pointer is exactly in front of its image.

NOTE: To eliminate friction, add sufficient weights to the hanger so that the coils of the spring are slightly separated.

NOTE: Before starting your observations, be sure the pointer is near the top of the scale. Adjust by moving the spring hanger or the scale up or down on the stand. The pointer does not need to be set on zero.

2. Record the position of the pointer on the first line on the data sheet table. Read the position as accurately as you can.

3. Add a 50 g mass to the hanger and weight already in place. Read and record the new position.

4. Continue adding masses (50 g at a time) until a total of 300 g have been added. Read and record the position at each step.

5. Remove the masses in equal 50 g steps and record the position at each step.

   CAUTION: Do not add more than 350 grams to the spring. The spring will exceed the elastic limit of the metal and will not return to its original shape. The spring constant would be altered and the spring ruined.

6. Convert the masses to weight (stretching force) in dynes. Record in the table.

7. Plot a graph of the data (Force vs. displacement).

8. Does the result of the experiment thus far indicate that Hooke's law is correct? Answer this question on the data sheet.

9. Calculate the difference in successive readings of the position of the pointer. Record in the table. This gives the deflection of the spring for each 50 g step.

10. Calculate the average deflection of the spring.

11. Use the average deflection of the spring to calculate the spring constant in dynes/cm. See Information Sheets (green, pages) for discussion of springs.

12. Add 300 g to the hanger on the spring. (The deflection is already recorded in the data table.)

13. Calculate the energy stored in the spring.

14. What is the average force that stretched the spring in step 12?

15. Calculate the work done is stretching the spring in step 12.

16. Compare the results of steps 13 and 15. $\frac{(\text{diff} \times 100)}{(\text{Energy})}$

17. Replace the large spring with the small one.

18. Record the position of the pointer.

19. Add masses in 10 g steps until you have added a total of 30 g to the hanger. Record the position of the pointer at each step.

20. Plot the data on the same graph as before.

21. Calculate the spring constant for this spring.

22. Is the slope of the graph greater or smaller than with the stiffer spring?

23. Is the spring constant larger or smaller than that for a stiffer spring?

24. Energy is stored in a stretched spring. What happens to this energy when the spring is released?

25. Replace the small spring with the large one.

26. Record the position of the pointer. (1st position)

27. Place 200 g on the hanger and record its position (2nd position).

    NOTE: If you gently lower the hanger to the 2nd position, the spring will not oscillate. However, if the hanger is held in the 1st position and suddenly released, it will fall to a 3rd position well below the 2nd and then oscillate for a long time.

28. Determine the 3rd position, approximately, after two or three trials.

29. Calculate the gravitational potential energy of the 200 g mass in the 1st position relative to the 2nd.

30. Calculate the amount of stretch the spring would have if all the gravitational potential energy were transformed to elastic potential energy.

31. Compare the results of step 28 and step 30.

    NOTE: In the 2nd position, 50% of the original gravitational energy is stored as elastic energy (see steps 15 and 16). If the 200 g mass is lowered gently, the other 50% is lost. If it is released suddenly, the other 50% becomes kinetic energy at the 2nd position.

32. How much kinetic energy is there in the 3rd position?

33. How much gravitational potential energy is there in the 3rd position (Hint: negative energy) relative to the 2nd position?

34. How much elastic energy is stored in the spring in the 3rd position?

35. How much total energy is there in the 1st position?

36. How much total energy is there in the 2nd position?

37. How much total energy is there in the 3rd position?

38. Compare steps 35, 36, and 37. Does this confirm the law of conservation of energy?

39. It was stated above that 50% of the original gravitational energy when lowered gently to the 2nd position was lost. Where did it go?

NOTE: Although some energy is lost as heat in the flexing of the spring, it is a negligible amount. A spring will oscillate a long time before the original energy is converted to heat and disapated.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 9

Title: SIMPLE MACHINES

Module Contents:
1. Mechanical advantage
2. Efficiency
3. Lever, inclined plane, and hydraulic jack
4. Modifications of basic machines
5. Compound machines

Program: This module has been prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to introduce words, terms, and concepts associated with simple machines. You, as an automotive or diesel mechanic, will spend much of your time repairing, adjusting, or operating the many mechanical, electrical, or hydraulic machines of industry or their controls. It is also necessary that you learn to speak the language associated with machines.

Producer: Gene Waring

Date Produced: October, 1976

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STUDENT INSTRUCTIONS

Module M 9 SIMPLE MACHINES

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define the following words and terms: machine, actual mechanical advantage, theoretical mechanical advantage, and efficiency.

2. Describe the lever by constructing simple diagrams of each of its three classes, showing input and output forces and lever arms.

3. List several examples of uses for each of the three classes of levers.

4. Describe the following modifications of the lever: wheel and axle, pulleys, block and tackle, and differential pulley by constructing diagrams of each showing input and output forces and movements.

5. Describe the inclined plane and the following modifications of it: wedge, cam, screw, and screw jack by constructing diagrams of each showing input and output forces and movements.

6. Describe the hydraulic jack by constructing diagrams showing input and output quantities.

7. Calculate the TMA, AMA, and efficiency for each of the basic machines and their modifications listed in objectives 4, 5, and 6; given the quantities required for the calculation.

8. From a list of input and output forces and movements, AMA, TMA and efficiency that describes a given machine, calculate those that are unknown and the work input and output.

9. Calculate the overall mechanical advantage of two or more machines set up in a "train" arrangement where one machine drives another.

10. State the principle of work (law of conservation of energy) as it applies to machines.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of simple machines. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook, plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 7). The information sheets cover subject matter that is presented briefly or not at all in some of the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read Chapter 6, sections 6.1-6.8 and sections 6.17-6.31, pages 137-144 and 151-169. Also read Chapter 11, sections 11.7-11.8, pages 273-277. (Note: Read either A or B, but not both)

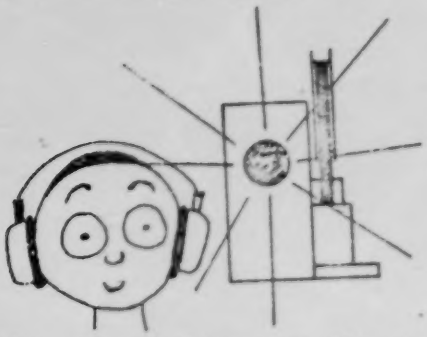
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read Chapter 7, sections 7.8-7.9, pages 85-87 and Chapter 12, section 12.5, pages 154-155.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read Chapter 10, sections 10.1-10.12, pages 118-141 and Chapter 15, section 15.4, pages 201-203.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read Chapter 12, sections 12.1-12.5, pages 168-183 and Chapter 13, section 13.4, pages 190-192.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read Chapter 12, sections 12.1-12.5 and 12.8-12.10, pages 175-183 and 188-193; and Chapter 14, section 14.2, pages 215-217.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. The Action of the Lever I, (EBE S-80824)
B. The Action of the Lever II, (EBE S-80825)
C. The Action of the Lever III, (EBE S-80826)
D. The Inclined Plane, (EBE S-80827)
E. The Pulley I, (EBE S-80828)
F. The Pulley II, (EBE S-80829)
G. The Screw, (EBE S-80830)
H. The Wedge, (EBE S-80831)
I. The Wheel and Axle, (EBE S-80832)

A 16 mm movie is available in the LRC. Its title is: From Muscle to Machine, (Educational film series) and is an excellent film supplement for this module. Try to arrange a viewing time when several of your classmates can join you. The LRC staff will show you how to operate the movie projector.

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving simple machine problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional proctice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are three experiments for most students in this module. They will give you practice in learning about mechanical advantage and efficiency, as well as, general problems associated with simple machines.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

Electronics students should perform two of the first three experiments and experiment 4.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for staisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module M 9 SIMPLE MACHINES

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The theoretical mechanical advantage of simple machines cannot be less than one.

T - F 2. The AMA of a machine is always less than the TMA.

T - F 3. A machine can be made to increase force and decrease speed at the same time.

T - F 4. A screw-jack is a modification of the inclined plane.

T - F 5. The work output of a machine is the work input plus the work done against friction.

6. On a block and tackle, an input force of 500 N, pulled through 18 m, raises a load of 4000 N while lifting it 1.8 m in 18 s. The TMA is:

a) 8
b) 10
c) 0.125
d) 0.1

7. What is the TMA of a differential pulley if the "wheel" radius is 8 in and the "axle" radius is 7.25 in?

a) 21.3
b) 7.63
c) 19.3
d) 1.1

8. The TMA of an inclined plane is 4 and its efficiency is 60%. What is the AMA?

a) 6.7
b) 24
c) 2.4
d) cannot be calculated

9. A differential pulley hoist is used to lift a 295 N engine, 2.5 m. If the efficiency is 75%, how much work is done to overcome the internal friction of the hoist?

10. The TMA of a handle on a hydraulic jack is 9. If the overall TMA of the lever-jack combination is 150, what is the TMA of the hydraulic mechanism?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 9 SIMPLE MACHINES

Question-Answer	If you missed this question, you are directed to these learning activities
1. F	I. Reading
2. T	I. Reading or II. Listening/Viewing
3. T	I. Reading or II. Listening/Viewing
4. T	I. Reading
5. F	I. Reading or V. Experiments
6. b	III. Solving Problems
7. a	III. Solving Problems
8. c	III. Solving Problems or V. Experiments
9. 246 J	III. Solving Problems or V. Experiments
10. 16.7	III. Solving Problems or V. Experiments

INFORMATION SHEET

Module M 9 SIMPLE MACHINES

Any mechanical device that aids man in doing work can be called a machine. There are two basic types: those that transform energy from one form to another, and those that transmit energy from one place to another. Six categories or classes of the two basic types are:

1. Devices in which the driving force is increased but the speed of the movement is decreased. Block and tackles, screws, incline planes, and some levers, gears and pulleys are examples of this class. This class of machine makes it possible to lift very heavy loads by applying relatively small forces.

2. Devices in which the driving force is decreased but the speed of the motion is increased. In situations where the driving force is applied to the short end of a lever or to the largest of two gears or pulleys the device becomes one of this type. This class of machine makes it possible to move objects very rapidly.

3. Devices that transmit mechanical energy or work without increases or decreases in the forces or speed of the movement. These devices merely provide a person with a more convenient way of doing work by pulling or pushing in a different direction or a more convenient place to apply the driving force. Examples are: using a single pulley to pull downward to lift a load; using a wire chain or load to apply a push or pull to another device some distance away (such as a hand choke on a car or a chain pull on a light switch); and using a drive shaft or cable to transmit rotary motion (such as a speedometer cable or drive shaft on a car). Idler gears, certain pulleys and hydraulic hoses are other examples.

4. Devices that transmit energy or material without doing work against external forces. These are normally called conduits. Examples are: water, oil, and gas pipelines; electric transmission lines; and heat ducts. Note that the incline plane is more than a conduit since work is done against the external force of gravity. Automobiles, trucks, trains, airplanes, and ships used in conjunction with roads, rails, airways, and waterways are conduits of energy and materials also. Compare the efficiency of moving materials through modern conduits to the methods used in ancient Egypt while building the pyramids.

5. Devices that convert energy from one form to another in which the final form is not mechanical energy (kinetic, gravitational, or elastic). Furnaces, boilers, solar collectors, refrigerators, electric generators, electric transformers, etc., are examples of this type.

6. Devices that convert energy from one form to another in which the final form is mechanical energy. Examples are: steam, gasoline, and diesel engines; steam, water, or gas turbines; rockets; guns and cannons; electric motors and solenoids; etc.

There are mechanical devices that do not transmit or transform energy and therefore are not classified as machines. Devices such as bolts, nails, rivets, staples, etc., are used to hold other objects together and are classified as fasteners. Devices such as cantilever beams, trusses, footings, etc., are used to carry the weight of other objects and may be classified as supports. Even though these devices exert forces or torques, once in place, there is no movement so they do not aid man in doing work.

The first three categories of machines are those that transmit energy and do work against external forces. These three catagories are classified as simple machines, the subject of this module. The other catagories are discussed in modules on fluid flow, electricity, and heat.

THE BLACK-BOX SIMPLE MACHINE

Simple machines have enough common aspects that a general description can be given without discussing specific distracting mechanisms. All simple machines have an input side and an output side. Suppose a certain mechanism is hidden in a black box as shown in figure 1. Two ropes hang from the box, one carrying a load to be lifted. The other rope is the input rope and is pulled downward to lift the load. The input force (Fi) is applied to the input rope and pulled downward through an input distance (si). The work input is Wki = Fi·si and the power input is the work input divided by the time required for the movement to take place (Pi = Wki/t).

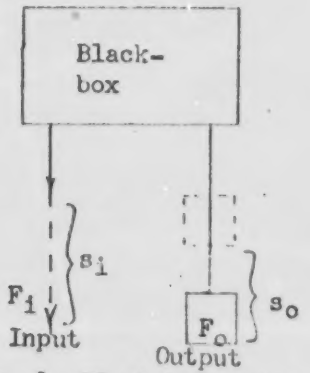


Fig 1. Black-box simple machine.

Similarily, the output force (F_0) resists the movement of the output rope. In this case, it is the weight being lifted. In other situations, it might be the resistance offered by a nail being pulled or the squeeze on the brake linings when brakes are applied. The output distance (s_0) is the distance that the object is being lifted (or offering resistance) moves during the time the input force moves throught the input distance. Work output is $Wk_0 = F_0 s_0$, and power output is $P_0 = Wk_0/t$. The time for both input and output power calculations is the same.

The mechanical advantage of the machine is given by the ratio of output force to input force. This ratio is called the actual mechanical advantage (AMA). Since the input force must overcome the friction within the machine as well as lift the load, the force ratio is a measure of the actual performance of the machine.

$$AMA = \frac{F_o}{Fi} \qquad 1.$$

The theoretical mechanical advantage (TMA) is what the ratio would be if the machine had no internal friction and is generally based on the geometry of the machine. (Some texts use the term ideal instead of theoretical so, IMA and TMA mean the same thing.) If there were no internal friction, the output work would equal the input work. The TMA then, is the ratio of input distance to output distance:

$$TMA = \frac{si}{s_o} \qquad 2.$$

The AMA can usually be increased by oiling the machine to reduce friction. As friction is reduced, the AMA increases to a value that approaches the theoretical value. Friction cannot be eliminated completely, so the AMA will always be slightly less than the TMA. Note: The TMA doesn't change since it is based on the internal dimensions of the machine.

A slightly different approach to the subject involves the law of conservation of energy or the principle of work. The work input is used, not only to lift the load, but part of it must do work to overcome friction:

$$Wki = Wkf + Wk_o \qquad 3.$$

Where Wkf is the work done against friction and is lost in the form of heat or sound. Since Wkf is never zero the ratio of Wk_o to Wki is always less than 100%. This ratio is called efficiency:

$$Eff = \frac{Wk_o}{Wki} \times 100 \qquad 4.$$

Another formula for efficiency is the ratio of power output to power input since time for the work to be done is the same on the output side of the machine as on the input side.

$$Eff = \frac{P_o}{Pi} \times 100 \qquad 5.$$

Equation 4 is the definition of efficiency. The formulas for work were given previously, so:

$$Eff = \frac{Wk_o}{Wki} = \frac{F_o\, s_o}{Fi\, si} = \frac{F_o/Fi}{si/s_o}$$

Hence: $$Eff = \frac{AMA}{TMA} \times 100 \qquad 6.$$

Equation 6 gives another formula for efficiency. The following example illustrates the use of the first six equations.

Example: A certain machine has an efficiency of 80%. A 1000 N load is lifted 3 m by an input force of 250 N. Find the: AMA, TMA, input distance, work input, work output, and work done against friction. Check the efficiency with equation 4.

Given: $F_o = 1000$ N $\qquad s_o = 3$ m

$Fi = 250$ N $\qquad Eff = 80\%$

$AMA = \frac{1000\ N}{250\ N} = 4$ Equation 1

$TMA = \frac{4}{.8} = 5$ Equation 6

$Si = (3\ m)(5) = 15\ m$ Equation 2

$Wki = (250\ N)(15\ m) = 3750\ J$ Definition of work

$Wk_o = (1000\ N)\ (3\ m) = 3000\ J$ Definition of work

$Wkf = 3750\ J - 3000\ J = 750\ J$ Equation 3

$Eff = \frac{3000\ J}{3750\ J} \times 100 = 80\%$ Check

If the time for the work to be done was known, the power input and power output could also be calculated.

The basic qualities of simple machines are presented as definitions or formulas in the first six equations. These equations apply to all simple machines. Equation 3 defines the TMA. Sometimes though it is difficult to measure the input and output distance. Since the TMA is based on the geometry of the machine, it can usually be expressed in simpler and more easily measured quantities. The specific formulas depend on the specific type of simple machine.

LEVERS

A quick stroll around a machine shop or an automotive repair shop would show many uses of the lever. It is, perhaps, the simplest and most widely applied mechanical device in industry. Levers fit all three of the categories of machines classified as simple machines. Usually, however, levers are divided into three classes in a different way.

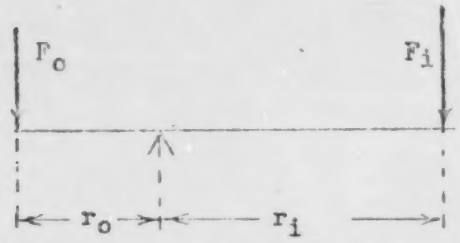


Fig 2. First class lever

The first class lever (figure 2) has the input force applied at one end of the lever, and the output force at the other. The fulcrum or pivot point is in between. Pry-bars are usually used this way. Equation 1 defines the AMA.

The input and output movements are along an arc and are different to measure. The same ratio is given by the ratio of lever arms, however:

$$TMA = \frac{r_i}{r_o} \qquad 7.$$

Notice that the fulcrum may be located at any point between the ends. The TMA will be very small (near zero) when the fulcrum is near the right end and very large near the left. Thus, we can say that:

$$0 < TMA < \infty$$

The symbol (<) means "less than: and (>) means "greater than." The symbol (∞) means infinity. A first class lever can have a TMA of any number between zero and infinity. A practical machine, however, cannot have a mechanical advantage of zero or infinity. What would this mean? An infinite MA means infinite movement on the input side with just slight movement on the output side. For practical purposes, the use of the word "infinity" to indicate the mechanical advantage ratio, will mean a large number perhaps 100 or 200.

Consider a TMA equal to one. Input and output movement must be equal. Lever arms must be equal. A TMA equal to more than one means greater input movement than output (greater input lever arm) but an input force less than the output force. A TMA less than one means less movement but greater force requirement on the input side.

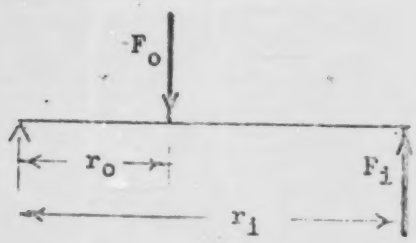


Fig 3. Second class lever

The second class lever is described in figure 3. The output force (load) being located between the fulcrum and the input force. Note that r_i is always greater than r_o, so the TMA is always greater than 1:

$$1 < TMA < \infty$$

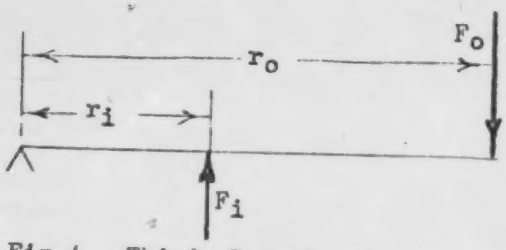


Fig 4. Third class lever

The third class lever is shown in figure 4. The input force is between the fulcrum and the load. Note that r_o is always greater than r_i in this one, just opposite to the second class lever. The TMA must be less than 1:

$$0 < TMA < 1$$

Most textbooks give several examples of each class.

WHEEL AND AXLE

Any wheel, crank handle, gear or pulley that is rigidly attached to an axle is called a wheel and axle. Figure 5 illustrates the machine, showing the input and output forces applied to ropes. The forces could be applied to gears or pulleys by other gears or V-belts instead. Figure 6 shows an end view of the wheel and axle. If all dashed lines are erased, you can readily see that the wheel and axle is really just a second class lever. It allows continuous movement in contrast to a regular lever used as a pry. Notice that the lever arms (r_o and r_i) are measured from the fulcrum (the axis of rotation). The TMA has the same formula as the lever (equation 7).

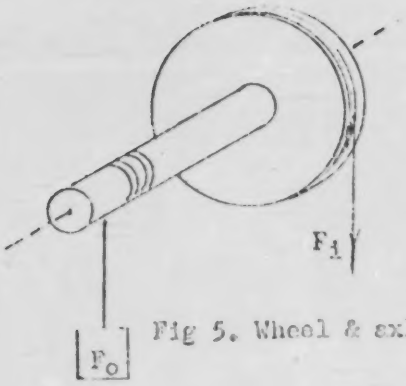


Fig 5. Wheel & axle

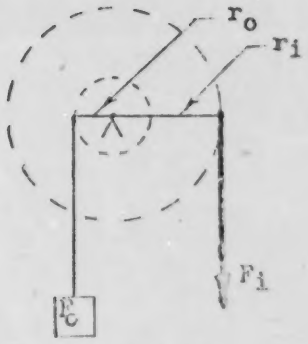


Fig 6. End view.

BLOCK AND TACKLE

Pulleys (sheaves) are sometimes arranged in blocks. Ropes or cables connect the pulleys to form a simple machine called a block and tackle. See figure 7.

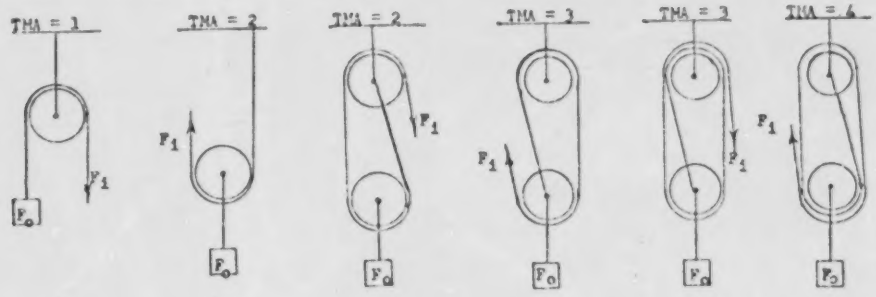


Fig 7. Block and Tackle

Arrangement (a) is a single pulley and allows a downward pull to lift the load (TMA = 1). Arrangement (b) is also a single pulley but an upward pull is applied. If the end of the rope moves upward 2 ft, one foot comes from the rope on each side of the pulley so the load is lifted 1 ft (TMA = 2). Arrangement (c) adds a pulley to allow a downward pull but is otherwise identical to (b). Turning (c) upside down gives arrangement (d). The load will lift 1 ft when the end of the rope is raised 3 ft (TMA = 3).

Arrangement (e) is the same as (d) except a second independent sheave has been added to the upper block to allow a downward pull. (Two ropes going over the upper block indicates two independent sheaves.) Arrangement (f) is the same as (e) except turned upside down. The TMA is increased to 4.

The TMA for block and tackles can easily be found by counting the ropes that directly support the load. You can draw the diagrams for block and tackles with more and more sheaves in both blocks, giving higher and higher mechanical advantage.

TMA = number of ropes directly supporting load 8.

DIFFERENTIAL PULLEY

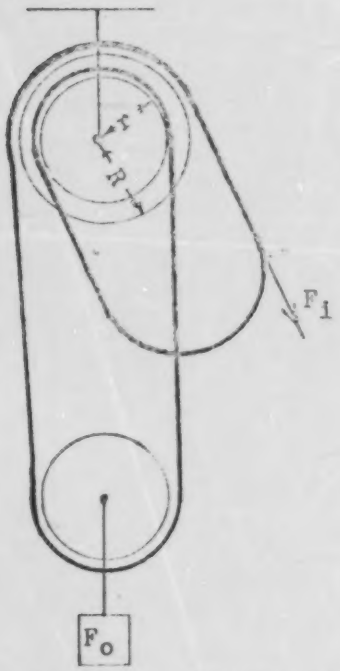


Fig 8. Differential pulley

A wheel and axle and a single pulley are used to form the differential pulley. They are connected by a single continuous chain as shown in figure 8. The chain rides in grooves so no slippage occurs.

If the input force pulls the chain through one circumference of the wheel and axle (a distance of $2\pi R$, a length of chain $2\pi R$ will unwind off the axle. At the same time, the chain on the left side of the single pulley will raise a distance $2\pi R$ pulled from above. So, the load will lift a distance of $\frac{1}{2}$ ($2\pi R$ - $2\pi R$ = $\pi(R-r)$. The TMA is therefore, the ratio of $2\pi R$ to $\pi(R-r)$ or, simplified is:

$$TMA = \frac{2\ R}{(R-r)} \qquad 9.$$

Notice that the smaller the difference in the size of the wheel and axle the greater the TMA.

INCLINE PLANE

Up to this point, the only simple machines that have been discussed have been modifications and variations of the lever. A second basic machine which has several variations is the inclined plane.

Less force is required to push a load up an incline against friction and a portion of gravity than it takes to lift it directly.

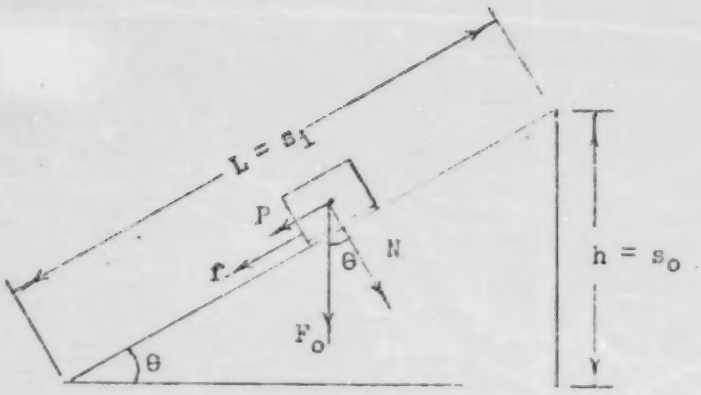


Fig 9. The inclined plane.

The output force is the load being raised and the output distance is the vertical rise (see figure 9). The input distance is the length of the incline. The input force is the force required to push the object up the incline. The TMA is given by equation 2, or:

$$TMA = \frac{L}{h} \qquad 10.$$

Note that this is the reciprocal of the sine of the angle of incline:

$$TMA = \frac{1}{\sin \theta} \qquad 10\ a.$$

The force (input) required to push the object up the incline is the sum of the frictional force ($f = \mu W \cos \theta$) and the component down the incline ($P = W \sin \theta$). So, the AMA, after substituting in equation 1 and simplifying, becomes:

$$AMA = \frac{1}{\mu \cos \theta + \sin \theta} \qquad 11.$$

so, the AMA depends only on the coefficient of friction (μ), and the angle of the incline (θ). Similarily, equation 6 for efficiency becomes:

$$Eff = \frac{1}{(\mu/\tan \theta) + 1} \times 100 \qquad 12.$$

WEDGES AND CAMS

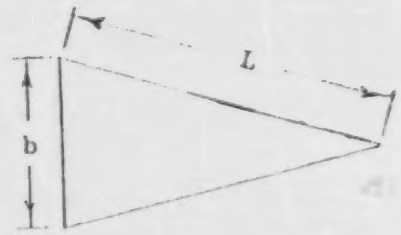


Fig 10. The wedge

The wedge is a double inclined plane. Its TMA is given by the formula:

$$TMA = \frac{L}{b} \qquad 13.$$

where b is the thickness at the butt or base end. The wedge is used for applying a force perpendicular to the direction it is

being driven, such as splitting logs. Note that the sharper the wedge, the greater the mechanical advantage.

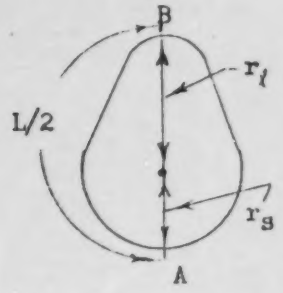


Fig 11. The cam

The cam is another variation of the incline plane. Cams are used to open and close valves and switches. The lift provided by the cam may not be proportional to the angle of rotation, so the mechanical advantage on some cams is variable. The lifting takes place as the cam slides against the push rod (for example) as it travels half the distance around the cam. The input movement is half the distance around the cam (L/2) and the output is the push rod movement (largest radius minus the smallest radius). The average TMA is:

$$TMA = \frac{L}{2(r\ell - rs)} \qquad 14.$$

SCREWS

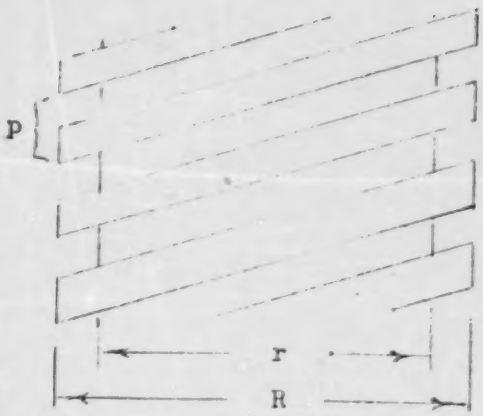


Fig 12. The screw

A screw is a modification of the inclined plane. The inclined plane is wrapped around a cylinder. A screw jack, for example, is used to lift various loads. The distance between threads is called the pitch (p). It is the distance the load is lifted or advanced in one complete turn of the handle. (s_0 = p)

The load effectively rides up the incline as the handle is turned. The input distance in one revolution is approximately the average circumference of the threads. The average radius (r) is halfway between the crest (outside) radius (R) and the root (inside) radius. The average circumference (input distance) is $\pi(R + r)$. The input distance in one revolution is actually the distance around, but spiraled upward one thread.

In one automobile bumper jack, the actual input distance was 45.2 mm, where the average circumference was 44.2 mm, an error of 2.2%. The error will generally be less since this jack had a high pitch to circumference ratio. For all practical purposes, the TMA then is:

$$TMA = \frac{\pi(R + r)}{p}$$ 15.

Note that this is the TMA for the screw only and does not include the mechanical advantage provided by the handle (lever). (The input lever arm is the handle length, the output is the average radius of the screw.) Equations 11 and 12 can be modified to fit the screw also, for example, the efficiency formula is approximately:

$$Eff = \frac{1}{[\mu p/\pi(R+r)] + 1}$$

Since the coefficient of friction is difficult to measure, this formula is not very useful. It is interesting, however, to note that the efficiency doesn't depend on the object being lifted. It depends only on the internal friction and the dimensions of the screw itself. The coefficient of friction must be large enough to prevent the weight from spiraling back down the screw, when the handle is released. The "angle" must be less than the angle of repose. Most texts state that this means the efficiency must be less than 50%. Screws are not very efficient machines.

WORM GEAR

A worm gear is a screw device that applies a force on the teeth of a large gear. It transfers rotation around one axis to slower rotation around an axis at right angles to the first (see figure 13). The screw must make one complete revolution to make the gear advance one tooth. The screw must turn as many revolutions as there are teeth on the gear to make the gear rotate one time. The TMA equals the number of teeth on the gear.

Fig 13. Worm gear.

HYDRAULIC AND PNEUMATIC MACHINES

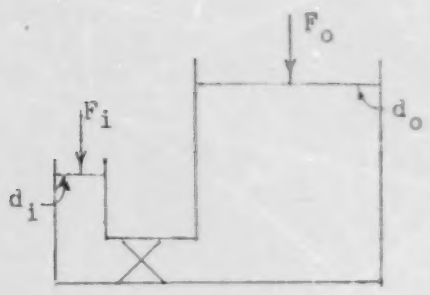


Fig 14. Hydraulic jack.

Hydraulic cylinders transfer forces and motion efficiently, smoothly, and (in the case of car brakes) evenly. Pascal's principle (see module P-4) states that "changes in pressure within an enclosed fluid is transmitted to every point within the fluid." Generally, this means that the pressure is the same on both input and output pistons (see figure 14). The larger piston will exert a larger force than a small

Fig 15. Hydraulic cylinder

one because of its larger area. (Pressure equals force divided by area.)

$$\frac{Fi}{Ai} = \frac{F_0}{A_0}$$

Where A is the area of the pistons. Since area is proportional to the square of the diameter, the theoretical mechanical advantage is given by the ratio of the square of the diameter:

$$TMA = \left(\frac{d_0}{di}\right)^2 \qquad 16.$$

The AMA and efficiency are given by formulas 1 and 6, respectively.

In the use of the hydraulic or pneumatic cylinders (see figure 14), there is usually no input piston as there is in the hydraulic jack. On the input side, pressure is applied by a hydraulic pump or by compressed air. The load the cylinder can lift is given by the pressure formula:

$$F_0 = PA_0$$

where P is the pressure applied.

COMPOUND MACHINES

In many applications of machines, two or more simple machines are used to form a compound machine. A screw mechanism is driven by a handle (lever) or by a gear. A hydraulic jack has a handle. Gears drive a cam shaft. There are many, many examples.

In each case, the output of one simple machine is the input of the second, the output of the second provided the input to the third, etc. It is easy to find the overall mechanical advantage or efficiency of such "train" arrangements of simple machines. Just multiply the quantity for the individual components. The overall TMA is:

$$(TMA_0) = (TMA_1)(TMA_2)(TMA_3)\ldots. \qquad 17\ a.$$

Similarily:

$$(AMA_0) = (AMA_1)(AMA_2)(AMA_3)\ldots. \qquad 17\ b.$$

and . . .

$$(Eff_0) = (Eff_1)(Eff_2)(Eff_3) \ldots . \qquad 17\ c.$$

Example: The AMA of the hydraulic mechanism of a jack is 6 and of the lever is 11. What is the overall AMA?

$$AMA_0 = (6)(11) = 66$$

Example: If the TMA of the jack of the parts in the previous example is 7 and 12 respectively, find the overall TMA and efficiency.

$$TMA_0 = (7)(12) = 84$$

$Eff = 6/7 = 85.7\%$ Hydraulic mechanism

$Eff = 11/12 = 91.7\%$ handle

$Eff_0 = (86\%)(92\%) = 78.6\%$

$Eff_0 = 66/84 = 78.6\%$ Check

GEARS AND PULLEYS (TORQUE TRANSMISSION)

The simple machines discussed previously all transmit amplified or reduced forces with corresponding inverse changes in linear motion. Gears and pulleys do not do this. When two gears are in mesh, one tooth exerts a force on another. These are action-reaction forces and are, therefore, equal. Also, since the movement of one tooth on one gear causes the same amount of movement of the other gear, the surface speeds of the gears are equal. The same is true of pulleys driven by flat or "V" type belts.

However, even though the forces are equal, they are not applied at the same distance from the axis of rotation. Torques are increased or reduced. Likewise, the rotational speeds are increased or decreased. Torque ratios and speed (rotational) ratios describe the transmission of power by gear or pulley trains.

A complete discussion of gears and pulleys, as well as, power transmission is included in module M-11, after the study of circular motion (module M-10).

PROBLEMS

Module M 9 SIMPLE MACHINES

1. The lever, inclined plane, and the hydraulic jack are the three basic simple machines. List several modifications or variations of each.

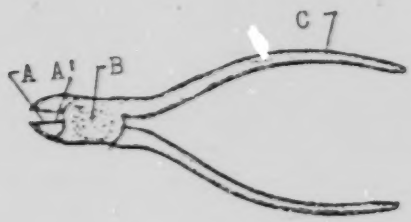
2. Make a list of several examples of each of the three classes of levers.

3. What is a force advantage? How is a speed advantage different? What is the mechanical advantage in each case?

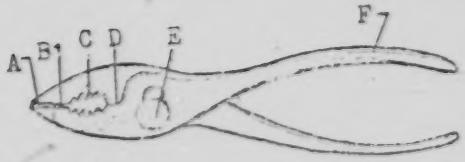
4. How does lubrication affect the TMA, AMA, and efficiency?

5. How does the amount of work done internally against friction affect the efficiency of a machine?

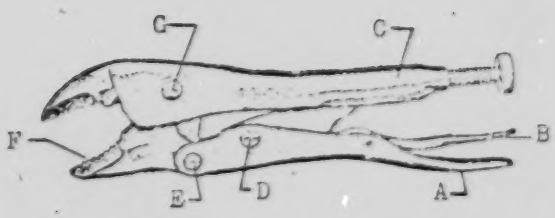
6. Discuss the following quantities and how they are related: work input, work output, work done against friction and efficiency.

7. 

Pliers, diagonal (dikes) wire cutters, and other similar clamping or cutting tools are two levers acting together. The fulcrum is at point B (see diagram). If the force is applied at point C, 10 cm from the fulcrum and a wire is cut at point A (near the center of the cutting edge) 1.7 cm from B, what is the TMA? What is the TMA if the wire is cut at A', 1.3 cm from B. What class lever is this?

8. 

The pliers shown may be used to grip objects at points A, B, or C and to cut wire at point D. The distances to the fulcrum E are: 4.5, 4, 2.5, and 1.5 cm, respectively. Find the TMA in each case if the force is applied at point F, 9 cm from the fulcrum.

9. 

The lower part (EDA) of the handle of a vise-grip pliers is a lever. It pivots at point E, applies a force on the toggle joint at point D by the action of a gripping force applied at point A. A snug grip on

the object being clamped can be accomplished by a 7 lb force at point A. If the distance EA is 5 in, and the distance ED is 1.25 in, what is the TMA of the handle? What class lever is it? What force will be applied to the toggle joint by a 7 lb input force if the lever is 95% efficient?

10. The toggle joint of the vise-grip pliers of problem 9 is a machine based on the lever. (See problems 13 and 15 of module M 3). Section ED of the handle serves a double purpose since it is one section of the toggle joint, also. The other section is DC. The force applied by the handle at point D is 26.6 lb. This exerts a force of 1270 lb on point E of the lower jaw along a line DE. What is the AMA of the toggle joint? If the efficiency is 90%, what is the TMA?

11. The lower jaw of the vise-grip in problem 9 is also a lever pivoting at point G. If a force of 1270 lb is applied at E, perpendicular to line GE, what force is applied to the object being clamped at point F? The distance GE is 1.5 in and GF is 1.88 in and the lever is 90% efficient. What is the TMA and the AMA?

12. A 7 lb force is applied to the handle of the vise-grip in problem 9. The output force is 911 lb. What is the overall AMA, TMA, and efficiency? Refer to problems 9, 10, and 11 and treat the vise-grip as a compound machine. Note: A larger input force will result in a greater output force but mechanical advantage and efficiency will remain unchanged. Adjustments of the screw at point C would change them slightly.

13. A shop vise has a screw of 6.25 mm pitch. The outside thread diameter is 2.12 cm and the root diameter is 1.60 cm. The length of the handle is 23 cm. Find the TMA of the handle and of the screw. What is the TMA for the compound machine? If the overall efficiency is 35%, how much clamping force is developed at the jaws if 150 N is applied on the handle?

14. A steering wheel on a car has a 16 in diameter. It drives a worm at the lower end of the shaft. The resistance is applied by the teeth of a large gear at 0.75 in from the axis on the worm. The steering wheel and the worm form a wheel and axle. What is its TMA? If the efficiency is 85%, what is the AMA?

15. A "Saginaw" steering mechanism is used instead of a plain worm gear on many automobiles. A ball bearing raceway is in the form of a screw wrapped around the steering wheel shaft. The bearings are caged in a block that moves along the shaft as the steering wheel is turned. Teeth on the

block mesh with and rotate a larger gear just like a worm gear does. The worm gear requires that the steering wheel be turned one revolution to advance one tooth on the large gear. The "Saginaw" requires two turns of the steering wheel. Seven complete revolutions of the steering wheel turn the large gear 90°. What is the TMA? There is less friction in the "Saginaw" than in a regular worm gear. If the efficiency is 65%, what is the AMA?

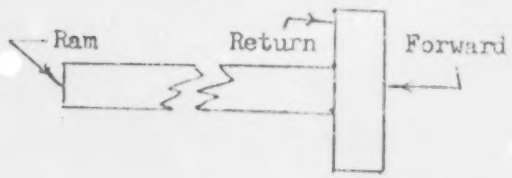
16. A 100 ton roll-bed hydraulic press used in a diesel shop, has a ram (output) that is double-acting to provide either push or pull. The hand-operated pump has a handle 22.5 in long and an output lever arm 1.25 in long. What is the TMA of the handle? If the handle is 90% efficient, what is the AMA? A force of 40 lb on the handle will exert what force on the input piston?

17. The shop press in problem 16 has a ram (output) piston diameter of 5.05 in. The two-speed pump (input) has a piston of 2.66 in diameter for fast travel and of 0.54 in to exert large forces. The switchover from one input piston to the other is accomplished by hydraulic pressure. Find the TMA of the hydraulic mechanism for each input piston. If the efficiency is 90% for the small piston, what is the AMA? A force of 648 lb on the small piston delivers what force to the ram piston?

18. The handle on the shop press of problems 16 and 17 can travel 25 in. This movement of the handle causes how much movement of the input piston? How far will the ram piston move in one stroke of the handle if the large diameter input piston is used? If the small piston is used?

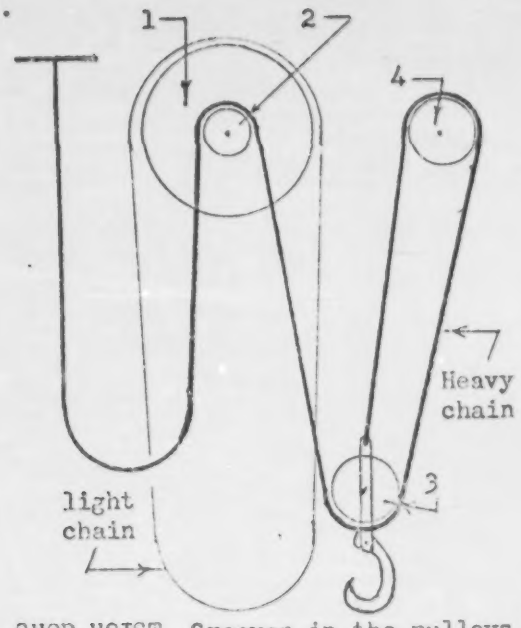
19. What is the overall TMA of the press in problems 16, 17, and 18, using the large input piston? What is the overall efficiency and AMA when the small input piston is engaged? This press has a 100 ton rating (ram force). What input force is required on the handle to achieve this force?

20. The 5.05 in ram (output) piston of the previous problems is on a 3 in shaft. When the ram is being lifted away from the work, the hydraulic pressure acts on the underside of the piston. Find the overall TMA of the compound machine if the large (input) piston in the pump is used. Note: Pressure is on the underside or return side of the piston.



21. A small differential pulley is used in the engine section of an automotive shop for lifting heavy equipment. If the two top pulleys have diameters of 14 cm and 13 cm, what is the TMA? If the efficiency is 65%, what input force will lift a 200 lb load?

22.



SHOP HOIST Grooves in the pulleys prevent the heavy chain from slipping.

A hoist in a diesel shop is shown in the accompanying diagram. Pulleys 3 and 4 form a block and tackle, while pulleys 1 and 2 form a wheel and axle. What is the TMA of the block and tackle? What is the TMA of the wheel and axle if the wheel (pulley #1) has a 16 in diameter, and the axle (pulley #2) has a diameter of 3 in? The hoist is operated by the small chain on the wheel (pulley #1). What is the overall TMA of the compound machine?

NOTE: This hoist moves along a beam and the beam can move the length of the shop. Heavy equipment can be moved to any point in the shop.

ANSWER KEY (PROBLEMS)

Module M 9 SIMPLE MACHINES

1. Lever: wheel and axle, pulleys, bell crank, gears.
   Inclined Plane: cam, wedge, worm gear, screw.
   Hydraulic Jack: hydraulic lift, hydraulic press, hydraulic pullers.

2. 1st class: pliers, rocker arm
   2nd class: wheelbarrow, nut cracker
   3rd class: tong, forearm

3. TMA >1, TMA <1

4. No effect, increases, increases

5. Greater the friction, lower the efficiency.

6. $Wk_i = Wk_o + Wk_f$, $Eff = Wk^o/Wk_i$

7. 5.9, 7.7

8. 2, 2.25, 3.6, 6

9. 4, 2nd, 26.6 lb

10. 47.7, 53

11. 912 lb, 0.8, 0.72

12. 130, 169, 77%

13. 24.7, 9.35, 231, 12 100 N

14. 21.3, 18.1

15. 28, 18.2

16. 18, 16.2, 648 lb

17. 5, 87.5, 78.7, 51 000 lb

18. 0.28 in, 0.016 in

19. 90, 1275, 81%, 157 lb

20. 10.7

21. 28, 11 lb

22. 3, 5.33, 16

EXPERIMENTS

Module M 9 SIMPLE MACHINES

PURPOSE: The purpose of these experiments is to study mechanical advantage and efficiency of three simple machines.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing, or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: The equipment for each experiment is listed at the beginning of the procedure section for each experiment. Check to see if it is all available before you start. Ask your instructor if you have questions about the equipment.

PROCEDURE: Experiment 1A "The Wheel and Axle"

Equipment:

1. Wheel and axle (Sargent-Welch #0752)
2. Thread or cord
3. Lab-stand, base and clamps
4. Weight hangers and slotted weights
5. Hooked weights

1. Assemble the wheel and axle apparatus by clamping it to the upper end of a lab stand.

2. Attach strings or thread to the largest and smallest diameter pulleys. Run the thread through the small hole and make a knot on the other side.

3. Attach a weight hanger to the thread on the large (input) pulley and a 500 g hooked weight on the thread on the small (output) pulley.

4. Pull the input rope through a distance of seventy-five (75) to one-hundred (100) centimeters and record the amount (input distance).

5. Measure the corresponding distance that the load is lifted (output distance).

6. Calculate the TMA from steps 3 and 4.

7. Attach a mass of 500 g one the output side of the system. Record its weight in dynes.

8. Attach a hanger and slotted weights on the input rope. Record force required to lift the load in dynes.

9. Calculate the AMA from steps 7 and 8.

10. Calculate the efficiency from steps 6 and 9.

11. Measure input distance and force required to lift a 1000 g mass through a distance of 10 cm.

12. Calculate the work output from step 11.

13. Calculate the work input from step 11.

14. Calculate the efficiency from steps 12 and 13.

15. Compare steps 10 and 14 by finding the (%) percentage difference.

PROCEDURE: Experiment 1B "The Worm Gear:

Equipment: 1. Worm gear (Sargent-Welch #0795)

On the worm gear apparatus:

1. Count the number of teeth on the large gear.

2. What is the TMA? (line 1)

3. Count the number of revolutions of the worm gear that are needed to cause one complete revolution of the large gear.

4. What is the TMA? (line 3)

5. Compare lines 2 and 4.

PROCEDURE: Experiment 2 "The Screw Jack"

Equipment:
1. Automobile bumper jack (screw-type)
2. 10 lb weight
3. Spring scale
4. Meter stick, ruler, vernier caliper

1. Remove the clip at the bottom of the screw shaft and raise the screw shaft out of the channel. This gives better access for taking measurements.

2. Measure the pitch of the screw (this can usually be done more accurately by measuring the distance of 10 or 20 threads, then dividing).

3. Measure the inside diameter of the screw threads.

4. Measure the outside diameter of the screw threads.

5. Calculate the average diameter from steps 3 and 4.

6. Calculate the TMA of the screw using steps 2 and 5. (See information sheets)

7. Measure the input length of the handle (length of handle from position of hand when using, also see diagram below).

8. Record the output length of the handle. (See diagram below. Assume the fulcrum is the cneter of the shaft. One-half of output force is at A, one-half at B.) Output of handle must equal the average radius of the screw. See step 5.

9. Calculate the TMA of the handle. (From steps 7 and 8)

10. Calculate the overall TMA from steps 6 and 9.

11. Calculate the distance circumscribed by the handle in ten revolutions. (Use step 7.)

12. Measure the movement of the lift bolt in ten revolutions of the handle or calculate it from step 1.

13. Calculate the overall TMA from steps 11 and 12.

14. Discuss any discrepancy in the calculations of the overall TMA. (Steps 10 and 13)

15. Place a 10 lb weight on the lift bolt and use a spring scale to measure the force required on the handle to lift it. Be sure the weight is lifted vertically. The spring scale should always pull tangent to the handle.

16. What is the overall AMA?

17. Calculate the efficiency of the bumper jack using steps 13 and 16.

18. Does the efficiency seem to be a reasonable value? Explain. What class lever is the handle?

PROCEDURE: Experiment 3 "The Hydraulic Jack"

Equipment: 1. The hydraulic jack (Sargent-Welch #W1044)
2. Vernier calipers, rulers

CAUTION: The mechanical advantage of the hydraulic jack is quite large. Moderate force on the handle will create pressures in excess of 5000 PSI in the hydraulic fluid. Since the output piston has a cross-sectional area of about 1 in^2, the force it can exert is about 5000 lb. DO NOT EXCEED 5000 PSI on the pressure gauge. Damage to the pressure gauge can result.

1. Measure the diameter of the input piston with a vernier caliper.

2. Measure the diameter of the output piston with a vernier caliper.

3. Calculate the TMA using the results of steps 1 and 2.

4. Measure the stroke of the input piston and multiply it by 10. DO NOT DISMANTLE. Use a ruler to measure the movement of the pin.

5. Measure the lift of the output piston in 10 strokes of the input piston.

6. Calculate the TMA using the results of steps 4 and 5.

7. Compare steps 3 and 6 by finding the percentage difference.

8. Measure the input length of the handle from the center of the place where the hand is placed (about 2 in from the end of the handle).

9. What class lever is the handle? Explain.

10. Measure the output length of the handle. DO NOT DISMANTLE. Measure from pin to pin.

11. Calculate the TMA of the lever (handle) from steps 8 and 10.

12. Measure the input stroke of the lever at the center of the place where the hand is placed. This is actually a distance along an arc. Measure as accurately as you can.

13. Calculate the TMA of the lever (handle) using steps 4 and 12.

14. Compare the results of steps 11 and 13 by finding the percentage difference.

15. Calculate the overall TMA from either the average or what you consider the best values of steps 3 and 6 and of steps 11 and 13.

16. Multiply the stroke of the handle (step 12) by 10.

17. Calculate the overall TMA from steps 5 and 16.

18. Compare the results of steps 15 and 17 by finding the percentage difference.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 10

Title: UNIFORM CIRCULAR MOTION

Module Contents:
1. Angular measurement
2. Angular velocity
3. Uniform circular motion
4. Centripetal and centrifugal force
5. Applications

Program: This module was produced especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: This module is an extension of the study of motion to objects traveling in circular paths. This type of motion is frequently encountered in industry and a knowledge of it is necessary for an understanding of the many diverse applications in industry. It is prerequisite to modules on power transmission, harmonic motion and wave motion. Practical applications are included in the problem sets of this module.

Producer: Gene Waring

Date Produced: November, 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module M 10 UNIFORM CIRCULAR MOTION

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. State the definition of the radian as a unit of angular distance, the symbol for angular distance, and the equation for radian measure.
2. State the definition of, and the symbol for, angular velocity.
3. Convert units of angular distance and angular velocity.
4. Distinguish between linear motion along an arc and angular motion associated with circular motion by stating the relationship between linear and angular velocity.
5. Calculate various linear and angular quantities by the use of definitions and relationships stated in objectives 1, 2, and 4.
6. State the formulas for centripetal acceleration and centripetal force in terms of both linear and angular velocity.
7. Apply Newton's three laws of motion to objects in uniform circular motion.
8. Distinguish between centripetal and centrifugal forces in terms of Newton's third law.
9. Solve applied problems in uniform circular motion.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of circular motion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7) directs you to the learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook, plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 7, sections 7.1-7.12, pages 173-188.

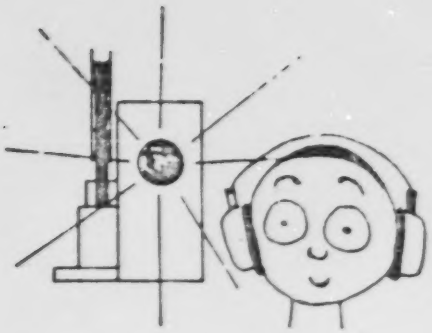
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 9, sections 9.1-9.3, pages 106-108, and chapter 1, section 1.7, page 11, and chapter 11, sections 11.1-11.2, pages 135-137.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall, Inc., 1st ed., 1974. Read chapter 11, sections 11.1, pages 145-147, and 11.3, pages 149-151, and Information Sheet (A-above).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 11, sections 11.1-11.2, pages 140-153.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read chapter 8, sections 8.1-8.5, pages 105-115, and chapter 11, sections 11.1-11.2, pages 158-160.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Inertial Forces, Centripetal Acceleration, (BFA Ealing 80-2140)

B. Circular Motion, (BFA Ealing 80-3080)

C. Velocity and Acceleration in Circular Motion, (BFA Ealing 80-2546)

III. Report: If you are a student in Electrical, Electromechanical, or Automotive or Diesel Technologies, make a report on how industry has solved problems of overcoming the centripetal forces that act on rotating equipment such as the armature of a DC motor. See instructions on page .

IV. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving circular motion problems. The problems from number five on are applied to your technology.

V. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

VI. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about uniform circular motion.

Read the laboratory instructions in this booklet (yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M-10) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUVATION TEST

Module M 10 UNIFORM CIRCULAR MOTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. An object is being whirled in a circle at the end of a string. If the string breaks, centrifugal force will cause it to "fly" radially outward (from the center of the circle).

T - F 2. Angular distance is related to linear (arc) distance by the formula: $s = \theta R$.

T - F 3. A radian is an angle at the center of a circle with an arc length equal to the radius of the circle.

T - F 4. Centripetal and centrifugal forces are an equilibrium pair of forces, act in opposite direction and thus: they cancel each other.

T - F 5. A particle in uniform circular motion has zero acceleration since its linear speed is constant.

6. A motor armature rotates at 1740 rpm. Its angular velocity in radians per second is:

a) 10 900 c) 29
b) 182 d) 30 300

7. A turntable rotates 0.55 revolutions in one second. How far linearly does the needle "travel" in one second? The groove is 15 cm from the center of the record. (Answer in centimeters)

a) 25.9 c) 51.8
b) 104 d) 8.25

8. A pulley drives a V-belt at a surface speed of 15 ft/s. If the pulley has a 2 in radius, what is its angular velocity in radians per second?

a) 45 c) 30
b) 7.5 d) 90

9. A small segment of wire conductor on the outer edge of a motor armature has a mass of 2.83 g. It is 10 cm from and lays parallel to the axis. Find the centripetal force on the wire segment if the motor rotates at 1720 rpm.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 10 UNIFORM CIRCULAR MOTION

Question-Answer	If you missed this question, you are directed to these learning activities
1. F	I. Reading or II. Listening/Viewing
2. T	I. Reading
3. T	I. Reading
4. F	I. Reading or III. Solving Problems
5. F	I. Reading or III. Solving Problems
6. b	III. Solving Problems or V. Lab Experiment
7. c	III. Solving Problems or V. Lab Experiment
8. d	III. Solving Problems or V. Lab Experiment
9. 918 000 dynes 9.18 N	III. Solving Problems or V. Lab Experiment

INFORMATION SHEET

Module M 10 UNIFORM CIRCULAR MOTION

ANGULAR MEASUREMENT

In the measurement of angles in triangles and other polygons, the angles are less than one revolution and many times are less than a right angle. Measurement of such angles are usually made in units of degrees. When many revolutions occur in a short time in rotating equipment, the angular measurement is counted in revolutions or radians.

The number of revolutions an object turns is the number of complete rotations it makes. The radian is defined by the following formula:

$$\theta = \frac{s}{R} \qquad 1.$$

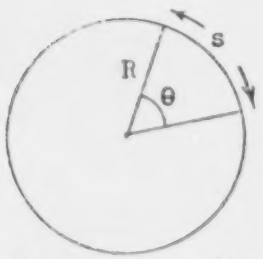


Fig 1. The radian.

where s is the arc subtended by the angle and R is the radius. The symbol θ is the greek letter theta. Refer to figure 1. Notice that when the arc distance is equal to the radius, the angle is one radian. There are 2π, or about 6.28 radians in one revolution. One radian is about 57.3°.

The arc distance and the radius must be measured in the same units. The units of the angle, therefore, are ft/ft, m/m, mi/mi, etc. The units cancel! The radian is just a name for this size of an angle. It doesn't act like other units do. If it is mixed in with other units, we can substitute ft/ft for it and cancel, effectively dropping it out.

EXAMPLE: A pendulum swings through an angle of 0.35 rad. Its length (radians) is 2.5 m. Through what arc length does the pendulum bob swing?

GIVEN: $\theta = 0.35$ rad

$R = 2.5$ m

SOLUTION: $s = \theta R = (0.35 \text{ rad})(2.5 \text{ m}) = (0.35 \text{ m/m})(2.5 \text{ m})$

$= 0.88$ m

Radians are simply dropped from the answer. Notice, since the radius is known, the swing of the pendulum in the example above is completely described by giving the angle (0.35 rad), an angular quantity. A complete description is also given when the arc distance (0.88 m), a linear quantity, is known.

ANGULAR VELOCITY

Since the position of an object moving in circular motion can be described by either linear or angular quantities, the velocity of the motion can also be described by linear or angular quantities. An electron going around the nucleus of an atom, a car going around a curve and a rope or chain unwinding off a pulley can best be described by the linear velocity (v) in ft/s or m/s of the object. However, the rotation of drive shafts, flywheels, gears and motor armatures, are better described by the angular velocity (ω) measured in rad/s or rpm.

Angular velocity is defined by the formula:

$$\omega = \theta/t \qquad 2.$$

The symbol (ω) is the greek letter omega (small case). Since there are 2π rad in one revolution and 60 s in one minute, then:

$$1 \text{ rad/s} = 2\pi/60 \text{ rpm}$$

EXAMPLE: Find the angle in radians that a flywheel turns through in 0.5 s if it is turning at 3000 rpm.

GIVEN: $t = 0.5$ s

$\omega = 3000$ rpm $= 314$ rad/s

SOLUTION: $\theta = \omega t = (314 \text{ rad/s})(0.5 \text{ s}) = 157$ rad

LINEAR AND ANGULAR RELATIONSHIPS

The relationship between linear distance (s) and angular distance (θ) is given by equation 1.. If this formula is rearranged it becomes:

$$s = \theta R$$

If both sides are divided by time, the left side becomes the linear velocity and the right is the angular velocity times the radius:

$$v = \omega R \qquad 3.$$

This formula provides the relationship between linear velocity and angular velocity. Angular velocity must be expressed in rad/s in this formula.

EXAMPLE: What is the linear speed of a point on the edge of the flywheel in the previous example if its radius is 40 cm? What linear distance does it turn in 0.5 s?

GIVEN: $t = 0.5$ s

$\theta = 157$ rad

$R = 40$ cm $= 0.4$ m

$\omega = 314$ rad/s

SOLUTION: $v = \omega R = (314 \text{ rad/s})(0.4 \text{ m}) = 126$ m/s

$s = \theta r = (157 \text{ rad})(0.4 \text{ m}) = 62.8$ m

CIRCULAR MOTION

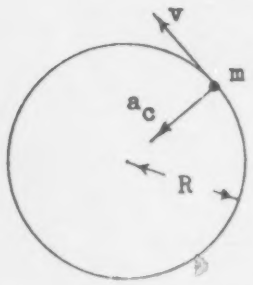


Fig 2. Circular motion.

When an object moves around in a circular path at a constant linear (or angular) velocity, it is traveling in uniform circular motion. Suppose the object has a mass m (see figure 2) and a linear velocity v in an object of radius R. The magnitude of the velocity will not change. Its direction, however, is changing constantly, always tangent to the curve. Notice the direction of the velocity at the instant shown. Suppose this is a mass swinging on the end of string. If the string should break at this instant, what direction would the object go? Since it is going in the direction of v, it would continue going in that direction. Its inertia would prevent it from going in any other direction since there are no external forces on it after the string breaks.

Newton's first law determines the direction the object will go if the string breaks. It also states that if the object is to follow a path other than a straight line, if it's going to follow the curved path, there must be an external force acting on it. It's easy to see that the force must be down and to the left at the instant shown (figure 2) if it is to curve downward away from a straight line path.

Newton's second law states what the magnitude of that force will be: $F = ma$. Many textbooks show how the acceleration is determined and its direction. The derivation is not repeated here. It has a magnitude of:

$$a_c = v^2/R \qquad 4.$$

and is a centripetal acceleration, meaning it is in a direction toward the center of rotation. In terms of the angular velocity it is:

$$a_c = \omega^2 R \qquad 4\text{ a.}$$

This formula is found by combining formulas 3 and 4 and simplifying.

EXAMPLE: A child sits 5 ft from the center of a merry-go-round rotating at 30 rpm. What is her linear velocity and acceleration? Check with both equations: 4 and 4a.

GIVEN: $R = 5$ ft

$\omega = 30$ rpm $= 3.14$ rad/s

SOLUTION: $v = \omega R = (3.14 \text{ rad/s})(5 \text{ ft}) = 15.7 \text{ ft/s}$

$a_c = \omega^2 R = (3.14 \text{ rad/s})^2 (5 \text{ ft}) = 49.4 \text{ ft/s}^2$

$a_c = \omega^2 / R = (15.7 \text{ ft/s})^2 (5 \text{ ft}) = 49.4 \text{ ft/s}^2$

The acceleration is very large because the angular velocity of the merry-go-round is very high. The child's inertia must be overcome so she holds on tightly to a cross bar. Her tendency to move in a straight line exerts an outward force (centrifugal) on the bar, bending it slightly. The bar exerts a reaction force on the child set up by its elasticity. This is an inward or centripetal force on the child. The friction between the child and the seat contributes some of the centripetal force, also.

The outward force (centrifugal) is a force on the parts of the merry-go-round and not on the child. The centrifugal force does not affect the child's motion. It is simply a reaction to the centripetal force required to cause her to move in circular motion. Newton's third law describes such action-reaction pairs of forces.

CENTRIPETAL FORCE

The magnitude of the force on a rotating object is found by substituting the formulas for centripetal force into Newton's second law:

$$F_c = \frac{mv^2}{R} \qquad 5.$$

or:

$$F_c = m\omega^2 R \qquad 5\text{ a.}$$

Remember that mass is found by dividing weight by the acceleration of gravity.

EXAMPLE: In order for the child (in the previous example) to keep from falling off the merry-go-round, what centripetal force is required? She weighs 50 lb.

GIVEN: $w = 50$ lb

$m = w/g = 50 \text{ lb}/(32 \text{ ft/s}^2) = 1.56$ slug

$v = 15.7$ ft/s

$w = 3.14$ rad/s

$R = 5$ ft

SOLUTION: $F_c = \frac{mv^2}{R} = \frac{(1.56 \text{ lb s/ft}^2)(15.7 \text{ ft/s})^2}{5 \text{ ft}} = 76.9$ lb

or: $F_c = m w^2 R = (1.56 \text{ lb s}^2/\text{ft})(3.14 \text{ rad/s})^2(5 \text{ ft}) = 76.9$ lb

The merry-go-round is turning very rapidly, the child must exert a force greater than her own weight. If friction between her and the seat is not substantial, she may have difficulty holding on at such a high speed.

Numerous applications of the centripetal force formulas are included in your text.

WORK

In the absence of friction, an object in uniform circular motion would continue forever. The centripetal force is perpendicular to the direction of motion at any instant. Recall the formula for work: $Wk = Fs \cos \theta$. In uniform circular motion, the angle (θ) between the direction of force and the direction of movement is always 90°. The cosine of 90° is zero. So, no work is done by centripetal forces.

No work is done by a uniform magnetic field in deflecting a beam of electrons. An electron orbits the nucleus of an atom in a friction free environment. The moon orbits the earth. The earth orbits the sun. If there were no friction, the moon and the earth would orbit forever. Since friction is small (tides) the orbiting of the moon will continue for a long, long time.

Work is done only when the angular speed changes. Tangential forces are required ($\theta \neq o$) to speed up or to slow down a rotating object.

PROBLEMS

Module M 10 UNIFORM CIRCULAR MOTION

1. Does the centripetal force do any work on an object in uniform circular motion? Explain your answer.

2. What force causes circular motion? What is the reaction of this force?

3. Explain the difference between linear (arc) distance and angular distance. Between linear velocity and angular velocity.

4. Why is the radian measure of angles the same for all measuring systems?

5. An electric motor is held down with four bolts. If you observe the motor from one end, the shaft turns clockwise. Is the force on all four bolts the same? Explain.

6. Express the following angles in radians: 30°, 45°, 60°, 90°.

7. Express the following angles in degrees: π rad, $\pi/6$ rad, $\pi/4$ rad, $\pi/3$ rad, $\pi/2$ rad, 0.28 rad, 0.73 rad

8. The angular velocity of the generator armature on an automobile varies from 1000 rpm at idle speed to 10 000 rpm at full engine speed. Express this range in radians per second. With what linear velocity does the commutator surface move past the brushes at both idle and full speed? The commutator diameter is 1.5 in.

9. What linear distance in miles does the commutator surface move past the brushes in one hour when the armature is rotating at full engine speed? (See problem 8).

10. A V-belt pulley on an alternator has a diameter of 3 in. It rotates at 2875 rpm. In 3 s it rotates through what angular distance in radians? What length of V-belt runs over the pulley in 3 s?

11. Starter to flywheel speed reduction is about 15 to 1 so the starter can apply large torques to the engine. What would be the angular velocity of a starter armature if the starter pinion failed to disengage from the flywheel? The engine speed is 3000 rpm. What is the normal armature speed if it turns the engine at 100 rpm?

12. A segment of wire (a part of the armature winding) weighs 0.01 oz and lays in one of the armature slots, 1.5 in from the axis. What is the force on this segment of wire if it is on a starter motor running at normal speed of 1500 rpm during starting? (Hint: mass equals weight divided by acceleration of gravity.) What would be the force on it if it is on the starter of problem 11 in which the starter pinion failed to disengage from the flywheel (45 000 rpm)? What would happen to the armature windings?

13. A fan blade on an automobile engine weighs 0.5 lb. Its center of gravity is 5.5 in from the axis. What centripetal force must the rivets provide to hold it on the hub? Its angular velocity is 3500 rpm. Fan blades have been known to break and fly through the hood of a car. If the blade described above breaks-off, what would be the linear speed of its center of gravity at the moment it breaks?

14. One hundred twenty centimeters of V-belt rolled over a pulley. If the pulley has a 14 cm diameter, what angle did it turn through?

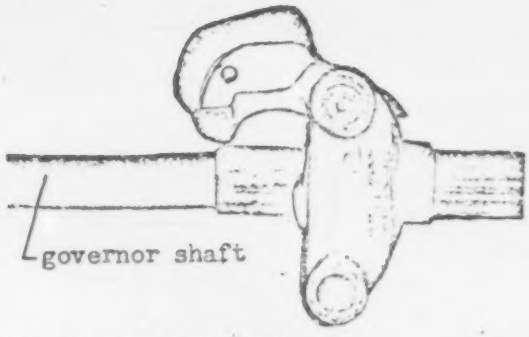
15. If the V-belt of problem 14 has a surface speed of 1.2 m/s, what is the angular velocity of the pulley? Its diameter is 14 cm.

16. The crest of a hill has a radius of curvature of 440 ft in a vertical plane. A 3500 lb automobile goes over the hill at 55 mi/h (80.7 ft/s). What is the centripetal force on the car? What force does the car exert on the road? At what speed would the automobile have to go for the centripetal force to equal the weight of the car? Note: The centripetal force is supplied by the weight of the automobile. At speeds requiring centripetal forces greater than the weight, the car would no longer make contact with the road surfaces at the crest of the hill.

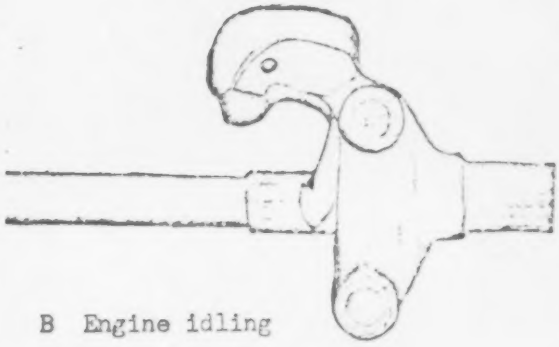
17. A 4000 lb car goes around an unbanked curve, a radius 800 ft. If the coefficient of friction between road and tires is 0.7, what is the maximum speed the car can have? Was it necessary that you know the weight of the car to answer this question?

INFORMATION (GOVERNORS)

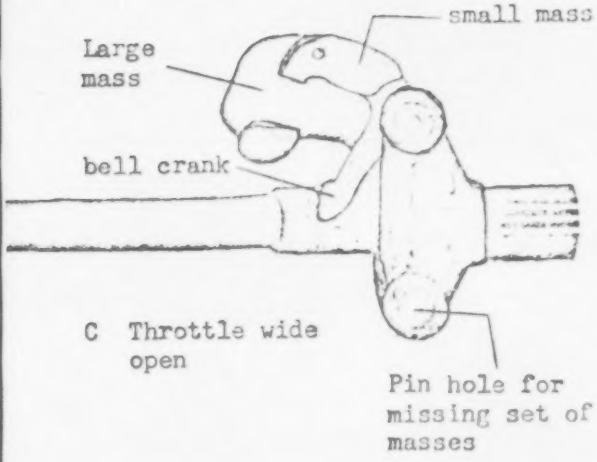
A governor shaft on a diesel engine operates at twice the engine speed. Two sets of masses, two springs and various linkages operate the fuel valve. One set of the masses is small (23 g) the other set is large (120 g). One of each is grouped together (see photos). The center of gravity of each mass is 3 cm from the governor shaft axis when the engine is operating at idle speed (shaft speed is 1000 rpm).



A Engine shut off



B Engine idling



C Throttle wide open

Pin hole for missing set of masses

The large mass remains in that position at higher speeds but the small mass moves outward to a position 3.6 cm from the axis at operating speed (shaft speed is 4200 rpm).

The masses pivot outward on a pin set at right angles to the governor shaft. The outward movement of the masses occur as they spin with the shaft. The small mass is in the form of a bell crank. The centripetal force on the masses is provided by tension in a spring, transmitted through several levers and along the shaft by a tube (riser) surrounding the shaft, and applied to the bell crank lever.

At slow speeds the small spring is not compressed very much and it holds the fuel valve in a slightly open position. If the engine (and governor shaft) speed up, the spring compresses more, reacting to the greater centripetal force required by the masses as they rotate faster. The movement of the spring as it compresses closes the fuel valve, slowing the engine. Reverse action takes place when the engine slows down below idle, opening the fuel valve. The large mass causes the small spring to react quickly so the speed of the engine remains nearly constant at idle speed.

At higher than idle speeds the large mass cannot move outward any further so operating speeds are controlled by the movement of the smaller mass. The small spring is compressed until the coils touch. A larger spring now takes over to exert the necessary centripetal force on the smaller mass.

When a load is applied to the engine (truck going up hill, for example) the fuel valve opens. It closes back when the engine reaches normal operating speed again. The reverse takes place if the engine exceeds operating speed such as a truck going down a hill.

18. At idle speed, both large and small masses on each side of the shaft, move together and have their center 3 cm

from the shaft axis. Together, they have a mass of 143 g and rotate at 1000 rpm. What is the centripetal force on them? If the bell crank lever is (effectively) 2.2 cm from the pin axis and the center of mass is 2.4 cm from it, what force must be applied by the springs on the lever to provide the necessary centripetal force? What total force must the springs supply at the bell crank lever for all four rotating masses?

19. At operating speed (4200 rpm), the small mass (23 g) has its center of gravity 3.6 cm from the shaft axis and 2 cm from the pin. Find the centripetal force on the small mass. The bell crank has an effective lever arm of 2 cm so it has a mechanical advantage of 1. What total force on the bell crank lever must the springs supply for the small masses of both sets at operating speed?

ANSWER KEY (PROBLEMS)

Module M 10 UNIFORM CIRCULAR MOTION

1. No, $\theta = o$, $F \perp s$
2. Centripetal, centrifugal
3. Hint: s and θ, v and ω
4. Arc and radius measured in same units which cancel
5. Force on left bolts due to reaction forces when armature accelerates. Force on right bolts at constant speed due to friction.
6. 0.52, 0.79, 1.05, 1.57
7. 180, 30, 45, 60, 90, 16, 41.8
8. 105 to 1050, 6.54 ft/s, 65.4 ft/s
9. 44.6 mi
10. 903, 113 ft
11. 45 000 rpm, 1500 rpm
12. 0.72 lb, 650 lb, be pulled out of slots and disintegrate
13. 962 lb, 168 ft/s
14. 17.1 rad
15. 163 rpm
16. 1620 lb, 119 ft/s
17. 91.3 mi/h
18. 47.0 N, 51.3 N, 103 N
19. 160 N, 320 N

REPORT

Module M 10 UNIFORM CIRCULAR MOTION

The following brief report should be completed by students in Electrical, Electromechanical, Automotive, and Diesel Technologies.

A segment of winding on the armature of a DC motor is about 4 in long. It lies in a slot in the laminated core, about 2 or 3 inches from the axis of rotation. In a large motor, it may be of 14 gauge copper wire. Such a motor operates at about 1750 rpm without a load. The segment of wire requires several pounds of centripetal force to keep it in its orbit about the axis. A number of such wires lay in the slots to complete the armature windings.

Naturally, the wire can move outward from the axis, only by taking up slack in the windings or by stretching the wires. Disintegration of the wires would begin if any of the armature parts move outward enough to catch on the stator parts. Great care must be taken to insure that this does not happen. Special problems arise in the construction of the commutator.

Look up in various technical books to find out more about the equipment and methods used to overcome the problems of holding an armature together. Write a short report (two or three paragraphs) describing cord bands, wire bands, glass tape bands, slots and wedges, and varnish and how they are used. Try to observe each of these on various armatures in the shop. (Your technical instructors may be able to show you cut-away models, etc.) One complete paragraph of the report should be devoted to the special problems associated with the commutator.

R. Rosenberg, Electric Motor Repair, Holt-Reinhart-Winston, 1960.

D. Braymer and A. Roe, Rewinding Small Motors, 3rd ed., McGraw-Hill, 1949.

K. Graham, Understanding and Servicing Fractional Horsepower Motors, American Technical Society, 1964.

C. Veinott, Fractional and Subfractional Horsepower Electric Motors, 3rd ed., McGraw-Hill, 1970.

EXPERIMENT

Module M 10 UNIFORM CIRCULAR MOTION

PURPOSE: The purpose of this experiment is to study circular motion. You will measure the centripetal force, angular velocity, radius, and mass of a rotating object. You will then test the formula for centripetal force that relates these quantities.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: Check to see if all the following equipment is available before you start.

1. Centripetal force apparatus (Spring balance type) Sargent-Welsh #0932.
2. Stop clock, (electric) 1/10 second.
3. Harvard trip balance (metric)
4. Meter stick

PROCEDURE: This experiment requires two people working together; one to swing the object in a circle and read the spring balance; the other to time a counted number of revolutions.

CAUTION: Examine the cord to make certain it is in good condition. Make sure it is well secured to the rubber stopper and to the spring scale. Frequent examination of the nylon cord will prevent the damage or injury that could occur if the rubber stopper should fly off through the lab. Ask your instructor if there is any doubt.

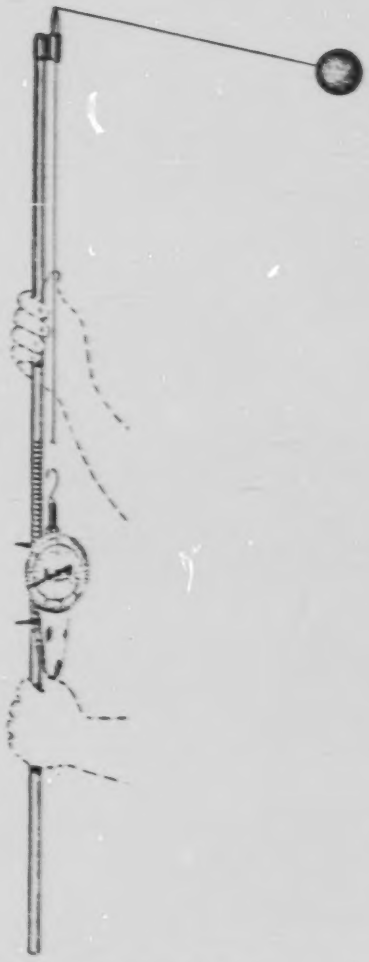
CAUTION: When the rubber stopper is being whirled around in a circle, do <u>not</u> rotate any faster than is necessary to cause the spring balance to read full scale. To do so will put too much strain on the nylon cord and could cause it to break.

1. Observe the stop clock. Notice that it can be operated by a remote switch when the toggle switch. (upper right) is in the off position. One revolution of the large hand is ten seconds. Six revolutions of the large hand is one minute.

2. Adjust the spring balance by sliding it up and down the rod so the cord length from rod tip to rubber stopper is about one-half meter.

3. One person should now practice rotating the rubber stopper above his head in a horizontal circle. (See figure) After a little practice, you will be able to rotate the apparatus at constant velocity. Constant velocity rotation is apparent when the spring scale remains steady. Best results are obtained if the spring scale reading is between 1.5 N and 2.5 N.

NOTE: Your hands should be held as shown in the figure. To prevent the tip of the rod from rotating in a large circle, one hand should be closer to the tip than the figure shows. Hold the apparatus so your fingers do not touch the string.



Centripetal force apparatus*

4. At the same time one person is practicing with the apparatus, the other should practice timing. Start the clock when the rubber stopper is moving toward you. When the clock is started, count "zero." Count "one" when stopper is moving toward you the next time around. Count "two" on the following cyle, etc. Stop the clock at the end of 15 revolutions.

NOTE: For an accurate timing, the clock will have to be started after the other person has the apparatus rotating at constant speed. He should indicate to the timer when he is ready.

5. You are now ready to take readings with the apparatus.

6. Set the clock on zero.

7. When the person rotating the rubber stopper says "start," measure the time for 15 revolutions.

NOTE: If the spring scale should indicate unsteady speed during a measurement, stop the timing and begin again.

* By permission from Sargent-Welch Scientific Company, Instructions for the use of # 0932 Centripetal Force apparatus.

8. Record the following measurements on the data sheet:

   A. The time for 15 revolutions.
   B. Spring balance reading.
   C. Radius of the swing. (Measure from the tip of the rod to the center of the rubber stopper. Pull the rubber stopper out until the spring balance reads the same as it did during the other measurements.)

9. From step 8A, calculate the angular velocity (ω) in rad/s.

10. Use the formula for centripetal force ($F = m\omega^2 R$) to calculate the mass of the rubber stopper.

11. Reset the apparatus so the distance from rod tip to rubber stopper is about 0.75 m.

12. Repeat steps 6 through 10 at the new setting. Exchange jobs for this measurement. Record data and calculations on the data sheet.

13. Reset the apparatus so the distance from rop tip to rubber stopper is 1 m.

14. Repeat steps 6 through 10 at the new setting after exchanging jobs again. Record on data sheet.

15. Calculate the average mass from the three calculated values.

16. Measure the mass of the rubber stopper on the Harvard trip balance. (Measurement with the spring balance by turning it upside down will not be accurate. Why?)

17. Compare the calculated value of the mass with the measured value. $\left(\frac{\text{meas} - \text{calc}}{\text{meas}} \times 100\%\right)$

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 11

Title: POWER TRANSMISSION

Module Contents:
1. Rotational dynamics
2. Gears and pulleys
3. Torque and power transmission
4. Torque and power measurement

Program: This module has been prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to study the efficiency with which rotating equipment transmits the energy produced by motors and engines. In rotating machines, the transmission of energy is accompanied by changes in torque and angular speed. (Changes in force and linear speed occurred in the simple machines of module M 9.) The study of gears and pulleys, torque and power measurement are included. Automotive and diesel technicians must have some knowledge of the rotating equipment that is used so extensively in these fields of industry.

Producer: Gene Waring

Date Produced: November, 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module M 11 POWER TRANSMISSION

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define angular velocity and angular acceleration. State the defining formulas and the units of each.
2. Define torque, horsepower and the units of each in both British and MKS systems.
3. Define speed ratio and efficiency. State the formulas for each for various gears or pulleys, including compound arrangements.
4. State the relationship between angular velocity and linear velocity.
5. State Newton's second law for rotation and the formulas for kinetic energy of rotation for a disc or ring.
6. State the formulas for power under steady velocity (linear or angular) conditions.
7. Describe the difference between spur, helical, bevel, herringbone, and worm gears.
8. Describe a pinion and gear, rack and pinion.
9. Describe the difference between a spur gear acting on an internal ring gear, and between a spur gear acting on an external ring gear.
10. Describe the purpose of an idler gear.
11. Calculate various problems using the formulas in objectives one through six.
12. State the formula for brake horsepower and solve various problems involving the Prony brake.
13. Describe the brake system, the cooling system, and the transducer system which provides the read out of horsepower or torque and angular speed of various dynamometers.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of power transmission. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 7) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test

(under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 8) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 6).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 9). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 6, sections 6.28-6.31, pages 162-169 and chapter 8 (all) pages 206-222.

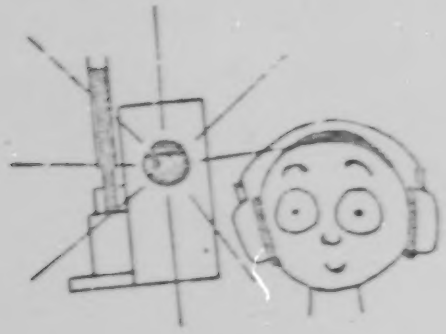
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 11, sections 11.1-11.7, pages 135-142, and chapter 7, section 7.10, page 87.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 11, pages 145-155 and all of chapter 12, pages 156-173.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 11, sections 11.2-11.4, pages 149-164; and chapter 12, pages 181-182; and chapter 8, section 8.2, pages 95-98.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 11, sections 11.1-11.7, pages 158-170 and chapter 9, sections 9.3-9.4, pages 130-132; and chapter 12, sections 12.6-12.7, pages 183-188.

II. Listening/Viewing: The following single concept film loop (8 mm) is available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the film. Ask the LRC personnel about this training.



A. Simple Machine: the gear, (EBE S-80831)

III. Outside Reading:

Flywheels, Post, R.F., Post, S.F., Scientific American, Volume 229, Number Six, December, 1973; pages 17-23.

This article describes the advances in mechanical design and materials used to manufacture flywheels. These advances make it possible to use giant flywheels to store energy in electric-power systems and smaller ones for the propulsion of cars, trucks, and buses.

This magazine is available in the Learning Resource Center.

IV. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 19). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving torque and power problems. The problems from number five on are applied to your technology.

V. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

VI. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about how power is measured in rotating equipment.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given.) Obtain a laboratory data sheet (M-11) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

VII. Guided Tour: Ask your instructor to arrange for a guided tour of the dynamometers in use in the shops on the Milford Campus. He will schedule a day when most of the students in your class can go along. Stops on the tour include:

LOCATION	POWER MEASURED	LOADING SYSTEM	COOLING SYSTEM	SIZE
Basic Mechanics	Engine Output	Water Turbine Brake	Water Cooled	Portable
Diesel Shop	PTO Output	Oil Turbine Brake	Water Cooled	Portable
	Engine Output	Water Turbine Brake	Water Cooled	Large
Automotive Shop	Rear Wheel	Water Turbine Brake	Water Cooled	Under Floor
	Brake System	Water Turbine Brake	Water Cooled	Motor Driven
	Transmission Loss	Disc Brake	Air Cooled	Engine Driven
Electrical Shop	Armature Shaft	Disc Brake	Air Cooled	Small (Motors)
	Armature Shaft	Electric Generator Brake	Air Cooled	Medium
	Armature Shaft	Magnetic Brake	Air Cooled	Large

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module M 11 POWER TRANSMISSION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Angular acceleration and centripetal acceleration are two names for the same quantity.

T - F 2. The moment of inertia of an object depends on how its mass is distributed relative to the axis of rotation.

T - F 3. When one spur gear drives another, the driver gear is called a pinion and the driven gear is a ring gear.

T - F 4. A pinion with 7 teeth will rotate four times faster than the ring gear it drives with 28 teeth.

T - F 5. One horsepower equals 33 000 watts.

6. A force of 28 lb is applied to a torque wrench with a handle 18 in long. The torque is:

a) 504 lb ft
b) 42 lb ft
c) 18.7 lb ft
d) 1.56 lb ft

7. What power is developed by a small electric motor turning at 1750 rpm if the torque is 0.5 m N?

a) 91.6 W
b) 875 W
c) 367 W
d) 36.7 W

8. The torque ratio of a pair of spur gears is 9. The efficiency is 90%, what is the speed ratio?

a) 1
b) 0.11
c) 8.1
d) 10

9. A flywheel is in the form of a disc 40 cm in diameter. Its mass is 20 kg. How much rotational kinetic energy does it have if it is rotating at 50 rad/s?

10. A small electric motor is being tested by a Prony brake. The pulley has a diameter of 1.125 in. The spring scales read 34.5 oz and 2.5 oz when the motor speed is 1775 rpm. Find the brake horsepower under this load.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 11 POWER TRANSMISSION

Question-Answer	If you missed this question, you are directed to these learning activities:
1. F	I. Reading
2. T	I. Reading or IV. Solving Problems
3. F	I. Reading
4. T	I. Reading or II. Listening, Viewing and IV. Solving Problems
5. F	I. Reading or VI. Experiments
6. b	I. Reading or IV. Solving Problems or III. Outside Reading
7. a	IV. Solving Problems and VII. Tour
8. d	IV. Solving Problems
9. 500 J	IV. Solving Problems and III. Outside Reading
10. 0.032 hp	VI. Experiment or IV. Solving Problems

INFORMATION SHEET

Module M 11 POWER TRANSMISSION

Module M 10 (Circular Motion) described rotational motion when the speed was not changing. Angular accelerations are produced by torques in much the same way linear accelerations are produced by forces (Newton's 2nd law).

Forces can create torques about the axis of rotation if the force has a tangential component. Centripetal forces are radial so they produce no torque since there is no lever arm. Centripetal forces are necessary for an object to go in a circle but create no tendency to change the angular speed.

To illustrate these points, suppose you were on a bicycle. Your feet are on the ground and you hold the front wheel off the ground by lifting the handle bars. A friend spins the front wheel to a high speed. Except for a small amount of friction in the bearing, the wheel continues to rotate with no tendency to speed up or slow down.

Lowering the bicycle to the ground sets up frictional forces between the tire and ground; a force tangent to the tire. On gravel roads, the wheel kicks gravel back toward your feet. On hard-top roads, the same tendency exists; a backward force on the road. The reaction to the force on the road is a forward force on the bicycle. The frictional force is tangent to the wheel and slows it down. Pedaling the bicycle or stepping on the brakes causes similar angular accelerations on the wheels. Accompanying the angular acceleration of the wheels is the linear propulsion or braking of the bicycle by the road through the medium of friction. On ice or when the drive wheels are elevated, the wheels spin but the propulsive force is lacking because a tangent force is lacking.

Since friction is involved between the road and tires (and in bearings), work must be done to maintain speed. The torque and power required to maintain constant speed or to accelerate must be transmitted from the pedals to the tire by a "power train" (gears and chain). In the case of automobiles and trucks, power is transmitted from the engine through a number of gears and drive shafts. In other rotating equipment, V-belt pulleys are used.

The discussion that follows includes the subjects of rotational dynamics, gears and pulleys, and power measurement.

ROTATIONAL DYNAMICS

Angular distance (θ) and angular velocity (ω) were defined in module M 10, but are repeated here for easy reference.

$$\theta = s/R \quad \text{(rad)} \qquad 1.$$

$$\omega = \theta/t \quad \text{(rad/s)} \qquad 2.$$

The relationship between linear velocity and angular velocity is:

$$v = \omega R \qquad 3.$$

Angular acceleration (α) is defined by the following formula:

$$\alpha = \frac{\omega - \omega_0}{t} \quad (rad/s^2) \qquad 4.$$

Where ω is the final angular velocity and ω_0 is the initial angular velocity.

EXAMPLE: A certain phonograph turntable (33 1/3 rpm) reaches full speed in 0.0942 s. What is the angular acceleration both in rad/s^2 and rev/s^2?

GIVEN: $\omega_0 = 0$

$\omega = 33\ 1/3\ rpm = 3.49\ rad/s$

$t = 0.0942\ s$

SOLUTION: $$\alpha = \frac{3.49\ rad/s - 0}{0.0942\ s} = 37.1\ rad/s^2$$

$$= 9.50 rev/s^2$$

Torque (T) is defined as force times the lever arm (see module M4). Lever arm is defined as the perpendicular distance from the fulcrum (axis of rotation) to the line of action of the force. Since the forces on rotating equipment are nearly always tangential, the lever arm is the distance from the axis to the point where the force is applied (radius). The formula for torque then is:

$$T = FR \qquad 5.$$

Its units are lb·ft or N·m.

Notice that the units have the same combination as work and energy units. They are not the same, however, and work units are usually distinguished by reversing the order: ft·lb or m·N = J. Technically, work is a scalar quantity; torque is a vector. They are not the same quantity even though torque and energy are both transmitted by rotating equipment. Movement is required if work is to be accomplished; torques can be applied with or without movement (rotation). A torque can be applied to a head bolt on an automobile engine with a torque wrench, for example. Work is being done as long as the bolt turns. However, the wrench handle could be turned to apply a torque to a tightened bolt, then wired in that position to the fender. The wrench could be left like that for five years and no work would be done, but a torque would be applied to the bolt throughout the entire time.

When an externally applied net torque is applied to a piece of rotating equipment, it will cause an angular acceleration. Newton's second law states that a net force causes a linear acceleration (F = ma). Newton's second law for rotation is very

similar but the angular acceleration depends on how the mass is distributed. A given torque will accelerate a given mass at a greater acceleration if the mass is in the form of a disc rather than a hoop. In a hoop, the mass is concentrated around the outer rim; in a disc, it is not. In a hoop, the entire mass is going at the same speed; in the disc, it is not.

Newton's second law for rotation is in the form:

$$T = I\alpha \qquad 6.$$

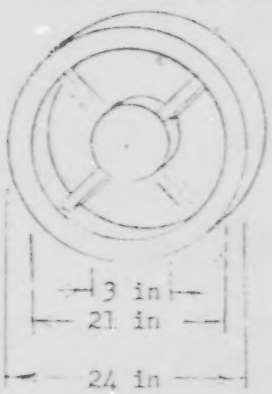
where I is called the moment of inertia. The moment of inertia depends on the distribution of mass within the rotating object. Formulas for the moment of inertia for a few simple objects are:

Table 1

Diagram	Object	Moment of Inertia
	Disc or solid shaft	$I = \frac{1}{2}MR^2$
	Hoop or pipe	$I = MR^2$
	Thin Rod	$I = 1/3\ ML^2$

EXAMPLE:

Fig 1



A flywheel has the shape shown in figure 1; a hoop connected to a hub by four spokes. The hoop weighs 100 lb, each spoke is 9 lb, and the hub (disc) is 15 lb. Find the angular acceleration of the flywheel when 80 lb·ft of torque is applied. Note: A force of 80 lb applied along the outer rim by a rope would produce this torque.

The moment of inertia of a compound arrangement like this is the sum of that for each part. The spokes present a special problem since they are not rotating about the end. Imagine they extend to the center. If they did, they would weigh 10.5 lb and would be 10.5 in long. The moment of inertia for the spokes can be calculated by the formula in table 1 for a thin rod. Then subtracting that for the imaginary part.

GIVEN: (Spokes) $Mi = W/g = 10.5\ lb/32\ ft/s^2 = 0.328\ slug$

$Mi = 1.5/32 = 0.047\ slug$ (Imaginary part)

$R = 10.5 \text{ in} = 0.875 \text{ ft}$

$Ri = 1.5 \text{ in} = 0.125 \text{ ft}$ (Imaginary part)

$I = 1/3\ MR^2 - 1/3\ Mi \cdot Ri^2$

$= 0.0837 \text{ slug ft}^2 - 0.00002 \text{ slug ft}^2$

$= 0.0835 \text{ slug ft}^2$ (each spoke)

GIVEN: (hub) $M = 0.469 \text{ slug}$

$R = 1.5 \text{ in} = 0.125 \text{ ft}$

$I = 1/2\ MR^2 = 0.0037 \text{ slug ft}^2$

GIVEN: (hoop) $M = 3.125 \text{ slug}$

$R = 11.25 \text{ in} = 0.938 \text{ ft}$ (average)

$I = MR^2 = 2.7495 \text{ slug ft}^2$

GIVEN: $I \text{ total} = 4(0.0835) + 0.0037 + 2.7495 = 3.09 \text{ slug ft}^2$

$T = 80 \text{ lb ft}$

SOLUTION: $\alpha = \frac{T}{I} = \frac{80 \text{ lb ft}}{3.09 \text{ slug ft}^2} = 26.0 \text{ rad/s}^2$

Notice that almost all the moment of inertia is in the outer rim. The hub could have been ignored, completely, and the spokes contributed only about 8%.

The kinetic energy of rotation also depends on the distribution of mass in a rotating object:

$$E_R = \tfrac{1}{2} I \omega^2 \qquad 7.$$

EXAMPLE: Find the rotational kinetic energy of the flywheel in the previous problem if it is rotating at an angular speed of 1200 rpm.

GIVEN: $\omega = 1200 \text{ rpm} = 126 \text{ rad/s}$

$I = 3.09 \text{ slug} \cdot \text{ft}^2$

SOLUTION: $E_R = \tfrac{1}{2} I \omega = \tfrac{1}{2}(3.09 \text{ slug ft}^2)(126 \text{ rad/s})^2$

$= 24\,500 \text{ ft lb}$

Power is transmitted against a constant resisting torque in much the same way as it is against a constant force of friction ($P = fv$).

$$P = T\omega \qquad 8.$$

This formula is important in the measure of torque or power when rotational motion is involved. Most power measuring devices (dynamometers) consist of a tachometer along with a meter that reads either power or torque. The other quantity can easily be calculated with equation 8.

Work done by a torque is the product of the torque and the angle turned through in radians:

$$W_k = T\theta \qquad 9.$$

GEARS AND PULLEYS

Gears and pulleys are used to transmit rotational motion and, at the same time increase or decrease torque and speed. Spur gears and pinions transmit power to an axis parallel to the drive axis (see figure 2). The smaller of two meshed gears is called the pinion. If the larger gear is quite a bit larger, it is usually called a ring gear. Notice that spur gears have the teeth parallel to the axis.

Fig 2

A helical gear and pinion accomplish the same purpose as spur gears. The teeth are set at an angle to the axis on the surface of a disc (see figure 3). The point of contact between teeth on helical gears slides along the tooth. This makes helical gears run quieter than spur gears. Helical gears are stronger since more teeth are meshed at all times.

Fig 3

A beveled gear and pinion transmits power to an axis prependicular to the drive axis (see figure 4). The teeth are on the surface of a section of cone.

Fig 4

A ring gear and worm (figure 5) does the same thing as a beveled gear, transmitting power at right angles to the drive axis. Worm gears are usually used when greater mechanical advantage is needed. Power is not readily transmitted backward from ring gear to worm unless they are specially designed. Worm gears are less efficient because the teeth slide continually on the worm (inclined plane). Worm gears have been used in automobile and truck differentials instead of a ring gear and pinion.

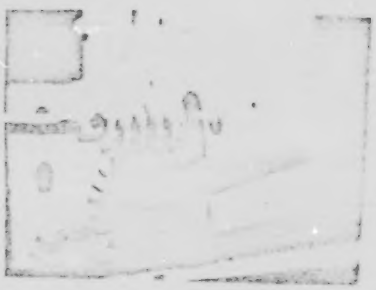


Fig 5

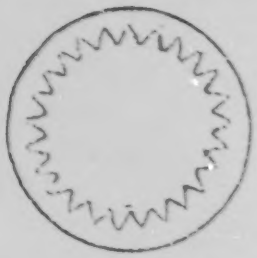


Fig 6

Fig 7

Spur and helical ring gears turn the opposite direction to the pinion if the teeth are external as in figures 2 and 3. An internal ring gear (figure 6) turns the same direction as the pinion.

Two spur gears will run the same direction, if they are in mesh with an idler gear (figure 7). If the two spur gears are the same size, there will be no mechanical advantage no matter what the size of the idler.

Fig 8

Figure 8 shows two sets of ring gears and pinion. Gear A drives gear B. Gear B and C are keyed or welded to the same shaft. Gear C drives gear D. Speed reduction occurs at the AB and CD combinations but not the BC combination. Gears B and C form a wheel and axle arrangement and rotate at the same angular speed.

Fig 9

Fig 10

Figure 9 shows a pinion running on a linear track called a rack. This combination is called a rack and pinion and transforms angular motion to linear motion. Either the rack or the pinion can be stationery. The pinion is attached to the carriage on a lathe, for example. The carriage moves along the rack. Pulleys connected by V-belts rotate the same direction (see figure 10). A twist in the belt will reverse the direction. Idler pulleys are used to create the proper tension in the belt.

SPEED RATIO

In the study of simple machines (Module M9), the important consideration was mechanical advantage. The multiplication (or reduction) of forces and linear motion was the prevailing concept. Forces applied to one tooth by another are not multiplied. Only action-reaction forces (Newton's third law) are acting when two teeth are in contact. The movement of one tooth forward on one gear causes one tooth to move on the other no matter what the size of the gears are.

Since the equal forces are applied at different distances from the axis when two different sized gears are in mesh, the torque may be multiplied or reduced. Angular speeds will also be different. It is the changes in torque and angular speed that is important in transmission of rotating motion by gears and pulleys.

The torque ratio (TR) is similar to the AMA of other simple machines:

$$TR = \frac{T_o}{Ti} \qquad 10.$$

The speed ratio (SR) (sometimes called speed reduction ratio or speed multiplication ratio if inverted) is similar to the TMA and is based on the geometry of the particular gears and pulleys. It is defined as the angular speed of the input gear to that of the output gear:

$$SR = \frac{\omega i}{\omega o} \qquad 11.$$

If the speed ratio is greater than 1, the gears or pulleys reduce the angular speed but torque is increased. It is a multiplication of angular speed if the speed ratio is less than 1 and torque is reduced.

The speed ratio is usually easier to find using geometric measurements rather than angular speeds. For pulleys:

$$SR = \frac{d_o}{di} \qquad 12.$$

Where di and d_o are the diameters of the input and output pulleys, respectively.

Using the ratio of the number of teeth (n) on a pair of gears is the easiest and most accurate method:

$$SR = \frac{n_o}{ni} \qquad 13.$$

Efficiency is the ratio of the torque ratio to speed ratio:

$$Eff = \frac{TR}{SR} \qquad 14.$$

This is similar to the ratio of AMA to TMA of module M9 on simple machines.

EXAMPLE: A simple spur ring gear and pinion have a speed ratio of 6. If the pinion has 9 teeth, how many does the ring have? If the efficiency is 75%, what is the torque ratio? The pinion has an input of 24 lb·ft of torque. What is the output torque of the ring? If the pinion is turning at 900 rpm, how fast is the ring turning?

GIVEN: SR = 6

Eff = 75%

ni = 9

Ti = 24 lb ft

$\omega i = 900$ rpm

SOLUTION: $n_o = (6)(9) = 54$ teeth equation 13.

$TR = (0.75)(6) = 4.5$ equation 14.

$T_o = (24 \text{ lb ft})(4.5) = 108 \text{ lb ft}$ equation 10.

$\omega_o = \frac{900 \text{ rpm}}{6} = 150$ rpm equation 11.

The solution to the problem can be checked by calculating the work accomplished in one minute.

CHECK: $Wk_o = T_o\theta_o = (108 \text{ lb}\cdot\text{ft})(2\pi(150)\text{rad} = 101\,800 \text{ ft}\cdot\text{lb}$ equation 9.

$Wki = Ti\theta i = (24 \text{ lb ft})(2\pi)(900) \text{ rad} = 135\,700 \text{ ft}\cdot\text{lb}$ equation 9.

$Eff = Wk_o/Wki = 75\%$

The check could have been made as easily using equation 8 for power and the formula: $Eff = P_o/Pi$.

The total speed ratio of combination of gears (or pulleys) such as shown in figure 8 is found by multiplying the speed ratios at each point where gears mesh.

$$SR_T = (SR_{AB})(SR_{BC})(SR_{CD}) \ldots \quad 15.$$

EXAMPLE: Find the speed ratio of the combination of gears in figure 8 if gear A has 7 teeth, gear B has 24 teeth, gear C has 9 teeth, and gear D has 30 teeth. Gear A is the input. If the angular speed of gear A is 1000 rpm, what is the speed of gear D?

GIVEN: $n_A = 7$

$n_B = 24$

$n_C = 9$

$n_D = 30$

$\omega_A = 1000$ rpm

SOLUTION: $SR_{AB} = 24/7 = 3.43$

$SR_{BC} = 1$ (wheel and axle)

$SR_{CD} = 30/9 = 3.33$

$SR_T = (3.43)(1)(3.33) = 11.42$

Gear D rotates 11.42 times slower so:

$$\omega_0 = \frac{1000 \text{ rpm}}{11.42} = 87.6 \text{ rpm}$$

POWER MEASUREMENT

Power is the rate at which work is done. Work is the result of a force acting through a distance or a torque acting through an angle. An engine or an electric motor must exert a torque through an angle for a period of time if it is to produce power. The angle and time are easily measured by using a tachometer to get the angular speed.

To measure the torque of a shaft rotating at high speed requires special equipment. The torque must be transferred to a stationery device so it can be measured. The device is called a dynamometer and consists of one of various kinds of brakes. The torque applied to the brake is transmitted to a read-out device (meter) calibrated to read force, torque, or horsepower. The brake can be set to load the motor or engine by any amount desired. The braking system may be a cradled electric generator, a water turbine, a magnetic (eddy current) brake or a friction brake. The read-out device may be simple spring scales, hanging weights, hydraulic pressure gauges, load cells, or strain gauges.

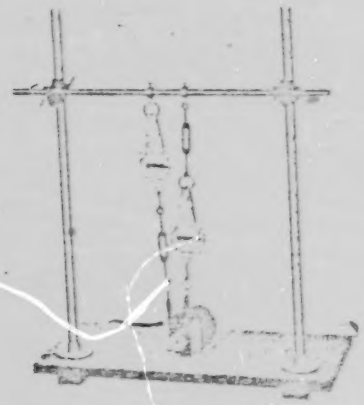


Fig 11 By permission from Sargent-Welch Scientific Company Cat. # 10670

PRONY BRAKE

The experiment that accompanies this module uses a simple Prony brake. A belt slides on a drum or pulley on the end of a motor shaft. Friction applies a braking torque to the motor. It increases the tension in the belt (see figure 11) on the right side and relieves tension on the left. Friction is measured by the difference in the spring scale readings. Friction applies a torque to the motor tangent to the drum or pulley. The lever arm is the radius of the drum. Angular speed is measured with a tachometer.

Equation 8 gives the formula for power. If the spring scale readings are in pounds, radius in feet and angular speed in rpm the formula (in horsepower) becomes:

$$P = \frac{2\pi R(T_2 - T_1)(\text{rpm})}{33\,000} \qquad 16.$$

If the spring scale readings are in grams, radius in centimeters and angular speed in rpm equation 8 (in watts) becomes:

$$P = \frac{2\pi R(T_2-T_1)(980)(rpm)}{60x10^7} \qquad 16a$$

The 980 converts grams (mass) to dynes (force). The 60 converts rpm to rps and the 10^7 converts erg/s to watts. More information about the Prony brake is included in the instructions for the experiment in this module (yellow pages).

DYNAMOMETERS

Dynamometers are power or torque measuring devices that have built-in tachometers. In fact, a dynamometer has other built-in equipment which usually enables a person to read the power or torque directly from a meter. If the meter reads one quantity, the other can be quickly calculated using equation 8.

The dynamometer converts the rotational torque to a stationery torque by using various kinds of brake systems. The brake system absorbs the energy transmitted to it from the engine or motor. Those dynamometers designed for continuous use are usually water-cooled. Air-cooled dynamometers are for intermittent use only.

Various dynamometers are in everyday use on the Milford Campus. They are used to measure the power or torque right off the engine or motor shaft. Some measure the power delivered to a power-take-off shaft on tractors. Others measure the power delivered to the rim of the rear tires on automobiles. One measures the torque delivered to the wheels by the brakes on an automobile. These are motor driven. One measures the loss of power and torque as energy is transmitted through an automobile transmission.

There is much to be learned by actually seeing the various kinds of equipment utilized in these dynamometers. Go on the tour when it is scheduled. (See learning activity number VII.).

PROBLEMS

Module M 11 POWER TRANSMISSION

1. Define work and torque. In what ways do the two quantities differ? How are units of work distinguished from units of torque?

2. What are some advantages of using helical gears instead of spur gears? Which is easier to manufacture?

3. What are some advantages of using a beveled ring gear and pinion instead of a ring gear and worm? Look up in reference books to find out what a hypoid ring gear and pinion is.

4.

A V-belt runs over a pulley as shown in the diagram where T_1 is greater than T_2. If the pulley drives the belt, which way is the pulley turning? If the belt drives the pulley?

5. The work done on a rotating object is the torque times the angle (in radians) that it turns through. How is the input work, output work and the work done against friction related?

6. How is the power output of an automobile engine, the power output of the transmission and the power losses within the transmission related?

7. A flywheel in the form of a disc has the same mass and radius as one in the form of a ring (spokes and hub have negligible moment of inertia). If the same torque was applied to each, which one will accelerate faster? Explain. If both flywheels were rotating at the same angular speed, which one has the most rotational kinetic energy? Explain.

8. A diesel engine (John Deere) has a flywheel which effectively is a solid cylinder (disc) with a heavy outer ring on it. The solid cylinder part weighs 99.6 lb and has a radius of 8.4 in. The outer ring weighs 78.5 lb and has an average radius of 8.8 in. Find the moment of inertia of each part and the total.

9. If the engine in problem 8 can develop an average maximum torque output of 800 lb ft in the speed range from 1500 to 2100 rpm, what minimum time could this engine accelerate the flywheel through the indicated speed range. The moment of inertia is 2.08 slug ft^2.

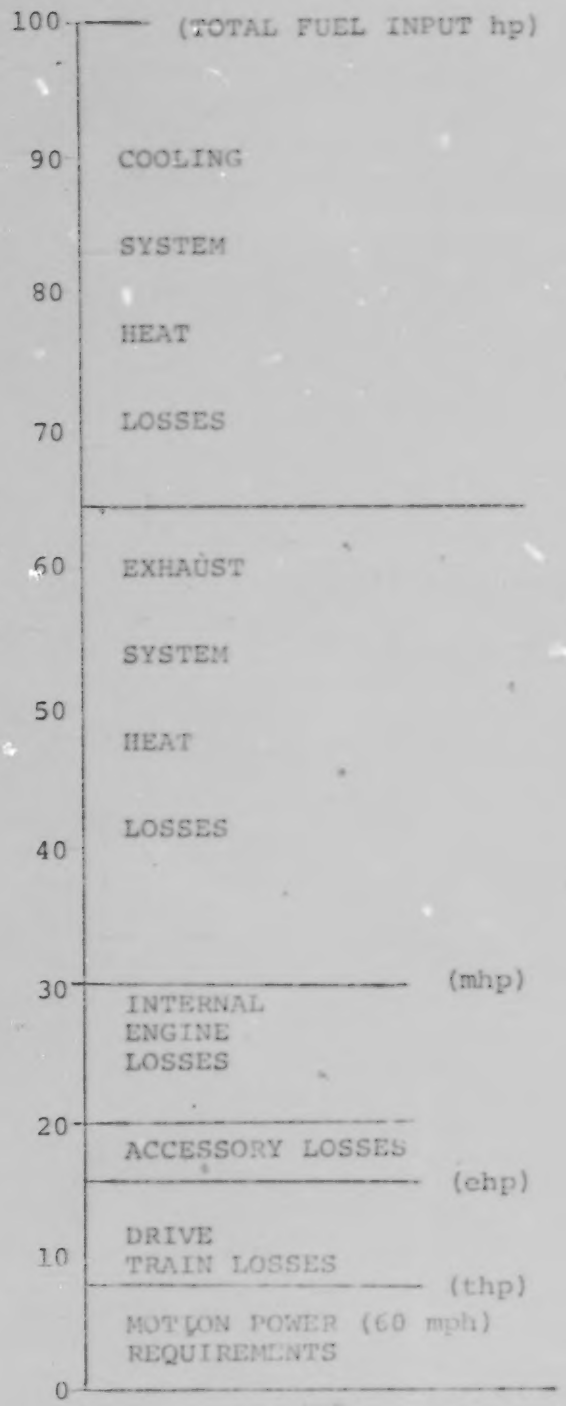
10. What rotational kinetic energy does the flywheel in problems 8 and 9 have when rotating at 1500 rpm? At 2100 rpm? What power is the engine developing if it can increase the speed of the flywheel from 1500 rpm to 2100 rpm in 0.163 s? Check your answer with the formula $P = \tau\omega$. The torque is given in problem 9 and the average speed is 1800 rpm.

INFORMATION: A typical medium-sized car going 60 mph gets 15 mi/gal. It uses the energy available in the gasoline at a rate of 180 hp at that speed. (There are 89 000 000 ft lb/gal) times speed (1 mi/min) divided by the mileage (15 mi/gal) divided by 33 000. Thirty-five percent of this power (63 hp) is lost in the form of heat through the cooling system and radiation from the engine. Another 35% is given off in the form of heat out the exhaust. The remaining power (54 hp) is the power actually developed in the form of forces doing mechanical work on the top of the pistons. If the engine was developing maximum horsepower, the power delivered to the pistons is called the indicated horsepower (ihp) of the engine. It is about 30% of the total fuel input when the engine is working at its fastest rate. Indicated horsepower is usually calculated by carefully measuring the average force on the pistons during the compression and power strokes. When the engine is not developing maximum power, the power developed on the pistons is called the mechanical input power (mhp) of the engine.

The power on the tires that propel the car is only a small part of the mechanical input horsepower. Power is used to do work on the engine internally, to operate accessories and to overcome the friction in the drive train. Only about 30% of the mechanical input horsepower (8-9% of the total fuel input) is available for propelling the car. The internal engine losses are due to the work that must be done to overcome the friction in the bearings, between piston rings and cylinder, etc. It includes the work done in pulling air-fuel mixture through the carburetor and manifold and pushing the exhaust gases out through the exhaust manifold, muffler, etc. In addition, the oil pump and distributor must be driven and the value springs must be compressed with power losses. Piston ring-cylinder wall friction accounts for the major portion of the internal losses.

Accessory losses include the operation of the engine fan, water pump, power steering, power brakes, air conditioner, and the generator or alternator. The work done in driving the generator or alternators depends on what electrical accessories (radio, lights, heater fan, windshield wipers, etc.) are being used. For more information about internal engine losses and accessory losses, review the problems for automotive and diesel students in module M 8.

When all the above losses are taken into account, the engine output horsepower (ehp) is determined. The engine output horsepower is about 50-60% of the mechanical input horsepower. (It is about 15% of the total fuel input power). When the engine is developing its maximum horsepower, the engine output horsepower is called the brake horsepower (bhp) of the engine.



Drive train power losses amount to about 35% of the mechanical input horsepower or about 50% of the engine output horsepower, (10% of the total fuel input). Drive train losses include power required to overcome friction in the transmission drive shaft differential and axle bearings, friction at the point where gear teeth mesh, flexing of the universal joints and motion in the drive shaft splines. In addition, power is required as the gears constantly stir the grease in the transmission and differential housings. Some power is used to drive the speedometer. Automatic transmissions increase the drive train power requirements. The temperature of the grease and oil makes a difference, also.

The power that arrives at the tire is called the tire (or road) horsepower (thp). The tire horsepower is about 9% of the original fuel input power or 35% of the mechanical input horsepower. It is about 50% of the engine output power.

Of the original 180 hp of fuel input of a typical car going 60 mph (15 mi/gal), 63 hp was lost as heat in the cooling system, 63 hp went out the exhaust, 16 hp was used to overcome internal engine losses, about 6 hp was used to operate accessories and about 16 hp were used to run the drive train. About 16 hp propels the car. Motion power includes work done in overcoming road friction, tire flexing, air resistance and friction in the front wheel bearings. It depends on tire type and amount of inflation.

If more accessories are turned on such as an air conditioner, greater accessory power is required. The accessory power will increase from 6 hp to about 11 hp to operate the compressor and air conditioner fan. The accelerator pedal must be depressed slightly to maintain a speed of 60 mph. In order to obtain an increase of 5 hp engine output, the total fuel input must increase by 16.7 hp. Remember that 70% of the fuel input is lost in the form of heat by the cooling and exhaust system. If the speed of the car remains the same, however, no other losses occur. The total fuel input power becomes 196.7 hp.

At 60 mph the car goes the same distance in the same length of time but greater fuel input power means fuel is going to be used at a faster rate. The mileage per gallon will drop from 15 mpg to 13.7 mpg. Note: Mileage per gallon equals fuel value (89 000 000 ft lb/gal) times speed (1 mi/min) divided by power (196.7 hp) divided by 33 000.

Notice that at any given situation all the power is being used. It is simply the rate at which work is done. This does not mean that the engine can't develop greater power though. If the acceleration pedal is depressed, the throttle opens and a larger amount of air-fuel mixture is able to get into the cylinders on each cycle. When this happens, a more powerful explosion takes place on the power stroke. A larger force is exerted on the piston and more torque is transferred to the tires. The car will accelerate or be able to climb a hill without losing speed. The fuel input power must increase (and fuel economy decreases) as the car accelerates or climbs a hill. Fuel is saved in the reverse situation when the car decelerates or coasts downhill.

If the car has accelerated to a higher speed, then the tire horsepower requirements are greater. Tire flexing takes place at a faster rate. Friction in the front wheel bearings and road friction forces probably won't change much but greater movement takes place per unit of time so more work must be done against friction. Air resistance increases with the square of the speed. The drive train losses increase because everything is operating at a faster speed. The engine is rotating faster too. Work done against internal friction is greater. The oil pump and water pump work against greater pressure heads. Nearly every energy consuming device on the car (except lights, radio, etc.) requires more power at higher speeds.

Working with the added requirements for higher speed back to fuel input, it is easy to see a loss in fuel

economy at higher speeds. Suppose the top speed of the car on level ground with no wind is 105 mph. The car will get about 9 miles per gallon at this speed. Total fuel input power is 525 hp with only 50 to 80 hp transmitted to the tires. Engine output power is maximum in this situation and would be equivalent to the brake horsepower of the engine (100 to 160 hp).

Naturally, all the above discussion refers to a typical situation. Particular automobiles may vary widely.

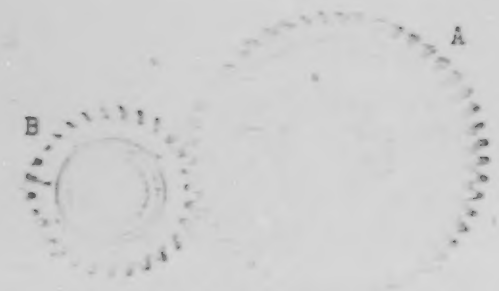
11. If the engine output of a car is 32 hp at an engine speed of 3025 rpm, what is the engine output torque? If 16 hp arrives at the tires, what is the efficiency of the drive train?

12. If the car in problem 11 is in high gear (direct drive), what is the speed ratio of the drive train? The ring gear and pinion in the differential have 63 and 14 teeth, respectively. What is the angular speed of the tires? If the tires have a 15 in radius, what is the linear speed of the car?

13. If the efficiency of the drive train in problems 11 and 12 is 50%, what is the torque ratio? The speed ratio is 4.5. How much torque is delivered to the tires? Calculate the force propeling the car using both the formulas: $\tau = Fr$ and $P = Fv$.

14. The car in the previous problems is in low gear which gives the transmission a speed ratio of 2.39. The differential speed ratio is 4.5. What is the overall speed ratio? What is the overall torque ratio if the efficiency of the drive train is 50%.

15. If gear A is the driver and is rotating at 1200 rpm, how fast is gear B turning? Gear A has 40 teeth, and gear B has 32 teeth. What is the speed ratio?



16.

If gear A is the driver, and is rotating at 800 rpm, how fast is gear C rotating? Gear B is an idler. What direction does gear C rotate if gear A rotates clockwise? Gear A has 32 teeth, B has 40, and C has 28. What is the speed ratio? What is the speed ratio if gear C is the driver?

17.

If the spur gear has 48 teeth and is 3.4 cm in diameter, and is rotating 3 rpm, how much time is required to rotate one-half revolution? The movable rack has 26 teeth in a length of 6.2 cm. How far will it move in one-half revolution of the gear? At what speed does it move? If the gear rotates clockwise, what direction does the rack move?

18. A worm gear rotates at 140 rpm. What angular speed does the ring gear it drives rotate if it has 45 teeth?

19.

A 3 in pulley on a motor drives a squirel-cage furnace fan with an 8 in pulley. What is the speed ratio for this V-belt system? If the motor turns at 1720 rpm, what speed is the fan rotating?

20. Refer to the diagram in problem 4. If the pulley diameter is 12 cm and it is rotating at 2000 rpm, what power is being transmitted by the pulley? T_1 is 60 N and T_2 is 15 N.

21. Refer to the diagram in problem 4. If the pulley diameter is 3.5 in and is rotating at 1250 rpm, what horsepower is being transmitted to the pulley by the V-belts? T_1 is 90 lb and T_2 is 40 lb.

22. Refer to figure 8 in the information sheets of this module. Gear A with 28 teeth drives gear B (49 teeth). Gear C has 32 teeth and drives gear D (40 teeth). What is the overall speed ratio? If gear A rotates at 1000 rpm, what is the angular speed of gear D? If gear A delivers a torque of 50 lb ft and the efficiency of the system is 75%, what torque is delivered to gear D?

23. A one-third horsepower motor operates at 1720 rpm. What torque does it deliver?

24. A one-fourth horsepower electric motor operates at 1700 rpm. The motor drives a gear reduction box. The output shaft of the gear reduction box rotates at 85 rpm. The gear reduction box is 60% efficient. With what net force can the machine pull a V-belt on a 3 inch pulley on the output shaft? What is the speed ratio of the gear box?

25. What torque can the force in the V-belt in problem 24 deliver to a 1 ft diameter pulley?

ANSWER KEY (PROBLEMS)

Module M 11 POWER TRANSMISSION

1. Work is force times distance moved, torque is force times lever arm. Work is a scalar, movement must take place. Torque is a vector, movement (rotation) may or may not occur. ft lb - lb ft, etc.

2. Quieter and stronger. Spur.

3. Force can easily be transmitted both directions.

4. ccw, cw

5. Wki = Wko + Wkf

6. Engine output equals transmission input. Pi = Po + Pf

7. Disc. $T = I\alpha$. If I is less α is greater. Ring. $E_R = \frac{1}{2}I\omega^2$. I is greater for a ring.

8.

cylinder	0.76 slug ft^2
ring	1.32 slug ft^2
total	2.08 slug ft^2

9. 0.163 s

10. 25.700 ft lb, 50 300 ft lb, 274 hp

11. 55.6 lb ft, 50%

12. 4.5, 672 rpm, 60 mph

13. 2.25, 125 lb ft, 100 lb, 100 lb

14. 10.8, 5.4

15. 1500 rpm, 0.8

16. 914 rpm, cw, 0.88, 1.14

17. 10 s, 4.8 cm, 0.48 cm/s, left

18. 3.11 rpm

19. 2.67, 645 rpm

20. 565 W

21. 1.74 hp

22. 2.19, 457 rpm, 82 lb ft

23. 1.02 lb ft

24. 31 lb, 20

25. 15.5 lb ft

EXPERIMENT

Module M 11 POWER TRANSMISSION

The Prony Brake

PURPOSE: The purpose of this experiment is to study the operation of the Prony brake and to determine the horsepower and efficiency under various loads.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the procedure section of these instructions.

INFORMATION: The Prony brake is a device for measuring the power output of an engine or motor. Power is defined as the rate of doing work. In equation form:

$$P = \frac{Wk}{t} \qquad 1.$$

where work is the product of a force applied, times the distance through which it acts.

The Prony brake has a belt that passes around a pulley or drum mounted on the output shaft of a motor. Each end of the belt is fastened to a spring scale. When the belt is tightened on the pulley, friction develops as the pulley turns. The frictional force drags the belt around relieving tension on the left side, increasing it on the right (see figure 1). The frictional force being overcome on the periphery of the pulley is the difference between the scale readings. The work being done against friction is the product of the frictional force times the distance through which it is applied. In one revolution of the pulley, the distance is circumference of the pulley - π d - where (d) is the pulley diameter:

$Wk = (F_1 - F_2)\pi d$ for one revolution.

For a number of revolutions, say N revolutions:

$Wk = (F_1 - F_2)\pi dN$

By permission Sargent-Welch Scientific Company. Cat # 10670

Since power is the rate of doing work (equation 1), we can use revolutions per second (rps):

$$P = (F_1 - F_2)\pi d(rps)$$

Since the power input is measured in watts, the output should also be measured in watts for easy calculation of efficiency. If the scale readings are in kilograms and the diameter of the pulley is measured in meters:

$$P(watts) = (F_1 - F_2)(9.81)\pi d(rps) \qquad 2.$$

where 9.81 is the acceleration of gravity in mks units.

Efficiency is the ratio of output over input:

$$Eff = \frac{P_o}{P_i} \; 100\% \qquad 3.$$

The efficiency of a motor is usually maximum at rated loads and less for loads either under or over rated load.

EQUIPMENT: Check to see that all the following equipment is available before you start. Ask your instructor if you have any questions about the equipment.

1. (1) one Sargent-Welch Prony brake, Cat. #4227-40
2. (2) two Spring scales (2000 oz capacity)
3. (1) one Leather belt
4. (2) two Turnbuckles
5. (1) one Wattmeter (0 to 1000 watts)
6. (1) one Tachometer
7. Vernier caliper
8. Various electrical connectors

PROCEDURE:

1. Use a vernier-caliper to measure the pulley diameter in centimeters. Record on the data sheet in centimeters and meters both.

2. Attach a turnbuckle to each scale and then hang each scale from hooks on the horizontal support rod. (See figure 1.)

3. Attach the belt to one turnbuckle, run it around the pulley, and then attach it to the other turnbuckle. The natural (not tanned) side of the belt should be against the pulley.

4. Position the horizontal support rod with the turnbuckles fully extended, as high as possible without putting a load on the scales.

5. Connect the motor lead to the load side of the wattmeter, the 5 amp terminal. Connect the wall plug to line terminals A and B of the wattmeter.

CAUTION: This motor is designed for intermittant use only as it will heat up rapidly after you turn it on in the next step. In addition, heat is produced by friction on the pulley and is conducted along the armature shaft to add to the problem. Take all readings as quickly as you can; then, turn the motor off.

CAUTION: Hold the tachometer, gently, with the rubber tip against the end of the motor shaft (in the next step). Slippage must not occur but excessive pressure will give a faulty reading by applying a load to the motor. The shaft of the tachometer must be parallel to the motor shaft for accurate readings.

6. With both scales reading zero, turn the motor on and measure the rpm with the tachometer. Record the rpm, scale readings and the wattmeter reading in line (1) one of table (1) one on the data sheet. TURN THE MOTOR OFF AS QUICKLY AS POSSIBLE.

7. Calculate the output power in watts, torque in Newton meters, and the efficiency and record in table (1) one. Do this before the next trial to let the motor cool as much as possible. This becomes more important after the first few trials.

8. Turn the motor on and adjust the turnbuckles to increase the load (as read on scale F_1) to 200 g. (See figure 1) Quickly read the tachometer, both scales and the wattmeter. TURN THE MOTOR OFF. Record data in table (1) one and calculate the output power, torque, and efficiency before the next trial as the motor cools.

9. Repeat step 8 to complete trials 3 through 10, increasing the load (on scale F_1) by 200 g each time. Make adjustments and record data as quickly as possible and shut the motor off between trials. Calculate the power output, torque and efficiency each time to let the motor cool between trials.

10. On the graph paper provided, plot rpm horizontally. Plot output power, torque and efficiency vertically on the same graph. Use colored pens for the curves for easy identification.

11. Disassemble the equipment and return to storage.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE--Milford Campus Milford, Nebr. 68405

Module:	P 2
Title:	FLUIDS I (STATICS)
Module Contents:	1. Pressure and vacuum 2. Bouyancy and specific gravity 3. Pascal's principle 4. The atmosphere
Program:	This module has been prepared especially for students in: 1. Automotive Technology 2. Diesel Technology
Purpose:	The purpose of this module is to study the principles of hydraulics. Hydraulic principles are utilized in fuel, lubrication, cooling, braking, steering systems and in numerous kinds of power equipment in the automotive and diesel industries. An understanding of hydraulic principles is essential. This module also serves as and introduction to courses in fluid power.
Producer:	Gene Waring
Date Produced:	January 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Co-ordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module- P 2 FLUIDS I (STATICS)

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define pressure and specific gravity.
2. State the formula for pressure in a liquid and define pressure head.
3. List the value of standard atmospheric pressure in various units and in various pressure head units.
4. Describe how both mercury and aneroid barometers work.
5. State the difference between absolute and gauge pressure scales and convert from one to another in various units.
6. Describe the manometer and the Bourdon gauge.
7. Use the manometer to measure head and convert to regular pressure units (British or metric).
8. State Archimedes' principle as it applies to both floating or submerged objects.
9. List the density of water in various British and metric units.
10. Determine the specific gravity of solid objects by weighing them both in air and water.
11. Measure the specific gravity of liquids using a hydrometer.
12. State Pascal's law.
13. Calculate various applied problems that involve the definitions and formulas of objectives 1, 2, 8, 10 and 12.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of fluids. You may feel that your experience will enable you to perform most

of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

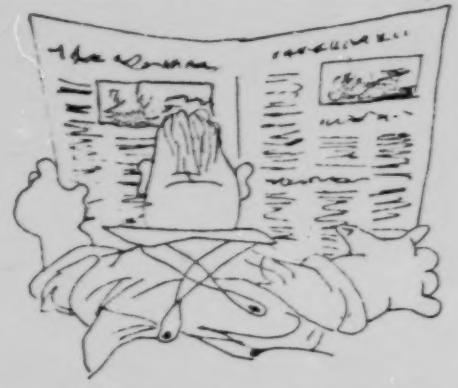
The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 6) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.



A. Information Sheet, Read the information sheets included in this booklet. They are printed on green paper (page). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., Read chapter 11, sections 11.1-11.12, pages 265-282 and chapter 12, sections 12.8-12.20, pages 302-314.

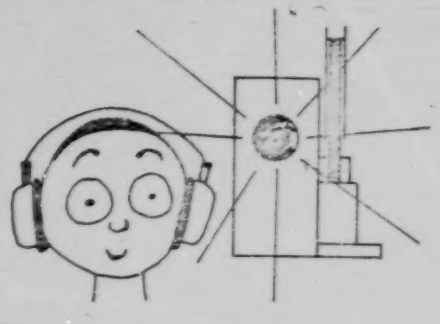
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 12, sections 12.1-12.9, pages 150-159.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 15, pages 196-207.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 13, sections 13.1-13.6, pages 184-197 and chapter 5, section 5.1-5.2, pages 58-61.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 14, sections 14.1-14.4, pages 212-220.

II. Listening/Viewing: The following film strip with cassette tape is available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the Hitachi sound projector and must precede the viewing of the film. Ask the LRC personnel about this training.



A. Basic Hydraulics (International Harvester B1-ST)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving hydrostatic problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are 2 experiments in this module. They will give you practice in learning about pressure and specific gravity.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (P-2) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower that 80% will require that you repeat the test. you must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module P 2 FLUIDS I (STATICS)

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The density of water is 62.4 lb/in^3.

T - F 2. An absolute pressure of 2 atmospheres is equivalent to 3 atmospheres gauge pressure.

T - F 3. A hydrometer sinks deeper in less dense liquids to displace its own weight.

T - F 4. The pressure under an object can be decreased by increasing the area the object rests on.

T - F 5. The pressure at the bottom of a container filled with liquid does not depend on the area of the liquid surface.

6. A solid object weighs 2.4 lb in air and 1.6 lb in water. Its specific gravity is:

a) 0.67 c) 0.33

b) 1.5 d) 3

7. Which of the following does not correspond to standard atmospheric pressure or pressure head?

a) 406.8 in (water) c) 30 in (mercury)

b) 1 g/cm^2 d) 1.013×10^5 N/m^2

8. What is the pressure in pounds per square inch measured with a mercury manometer if the levels are 21.2 in and 9.3 in? The density of mercury is 0.49 lb/in^3.

a) 187 c) 5.8

b) 57.1 d) 0.84

9. A force of 700 N is spread over an area of 35 cm^2. What is the pressure in newtons per square meters?

a) 200 000 c) 2000

b) 20 d) 0.05

10. The specific gravity of alcohol is 0.8. The difference in levels in an alcohol manometer is 16.5 cm. What is the pressure in newton's per square meter?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module P 2 FLUIDS I (STATICS)

Question-Answer	If you missed this question, you are directed to these learning activities
1. F	I Reading (Information Sheet)
2. F	I Reading
3. T	I Reading or IV Experiment
4. T	I Reading or II Listening/Viewing
5. T	I Reading or II Listening/Viewing
6. d	III Solving Problems
7. b	I Reading
8. c	III Solving Problems or IV Experiment
9. a	III Solving Problems
10. 1290 N/m^2	III Solving Problems

GRADING

NUMBER WRONG	GRADE
0	100
1	90
2	80
3	70
4	60
5	50
6	40

INFORMATION SHEET

Module P 2 FLUIDS I (STATICS)

Whenever a force is applied to an object, it is distributed over an area and a stress is set up in the object. If the force tends to compress the object, the stress is called pressure. It is defined by the formula:

$$P = \frac{F}{A} \qquad 1.$$

The pressure can be changed by changing either the force or the area.

Example: A 180 lb man stands with all his weight on one heel of one shoe. If the heel has an area of 8 in^2, what is the pressure on the floor under his heel?

Given: $F = 180$ lb
$A = 8$ in^2

Solution: $P = F/A = 180$ lb$/8$ $in^2 = 22.5$ lb$/in^2$

Example: Suppose the man in the previous example rocks back so his weight is on the back edge of his heel, an area of 0.5 in^2. What is the pressure?

Given: $F = 180$ lb
$A = 0.5$ in^2

Solution: $P = F/A = 180$ lb$/0.5$ $in^2 = 360$ lb$/in^2$

PRESSURE IN LIQUIDS

The pressure in a liquid that is due to its weight only is easily determined. Figure 1 shows a cylinder partially full of liquid where h is depth. The cylinder has a cross-sectional area A. The pressure on the bottom of the cylinder due to the weight of the liquid is given by equation 1. The force is the weight of the liquid.

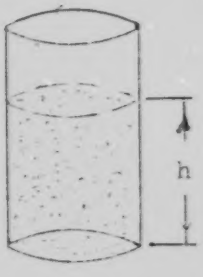


Fig 1. Pressure in liquid

Weight is given by the density formula ($W = DV$) where V is the volume. For objects of uniform cross-section throughout the entire length, the volume is given by the formula: $V = Ah$. Combining these formulas gives: $P = F/A = DV/A = DAh/A$. Since the area cancels, the formula for pressure in a liquid is:

$$P = Dh \qquad 2.$$

Where D is the weight density and h is the depth. The pressure does not depend on the area of the container. The pressure in water, for example, is the same at a given depth in the middle of a lake as it is in a quarter inch tube. The density of course must be the same in both places.

If you work a problem with mass density given instead of weight density the formula is:

$$P = dgh \qquad 2a.$$

Where g is the acceleration of gravity (9.8 m/s^2). Equation 2a is usually used with metric units while equation 2 is used with British.

Example: Find the water pressure at the bottom of a swimming pool at a depth of 12 ft. The density of water is 62.4 lb/ft^3.

Given: $D = 62.4\ lb/ft^3$
$h = 12\ ft$

Solution: $P = Dh = (62.4\ lb/ft^3)(12ft) = 749\ lb/ft^2$
$= 5.2\ lb/in^2$

Example: Find the water pressure in newtons per square meter at a depth of 76 cm in mercury. The density is 13.6 g/cm^3.

Given: $d = 13.6\ g/cm^3$
$g = 980\ cm/s^2$
$h = 76\ cm$

Solution: $P = dgh = (13.6\ g/cm^3)(980\ cm/s^2)(76\ cm)$
$= 1.01 \times 10^6\ dynes/cm^2 = 1.01 \times 10^5\ N/m^2$

Pressure in a fluid always "obeys" the following rules:

1. The forces a fluid exerts on a submerged surface or wall of the container always acts in a direction perpendicular to the surface or wall.

2. At any depth in a fluid, the pressure is the same in all directions.

PRESSURE OF THE ATMOSPHERE

The pressure of the atmosphere is due to the weight of the air. It is not as easy to calculate, however since there is no definite surface at the top and the density changes with altitude. About half the air is below the three mile altitude and 99% is lower than nineteen miles. The pressure at sea level is 14.7 lb/in^2 and the density is 2.2 lb/yd^3. Both quantities decrease to nearly zero at 20 miles altitude.

Pressure of the atmosphere is measured with a barometer. A mercury barometer consists of a tube closed at one end and filled with mercury. When the tube is inverted and the open end

submerged in a container of mercury, the air pressure supports a column of mercury (Hg) in the tube about 30 inches high. The atmosphere will support a column of water in a similar way of about 34 ft. Equation 2 can be used to calculate these heights.

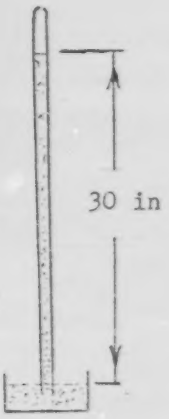


Fig 2. Mercury barometer

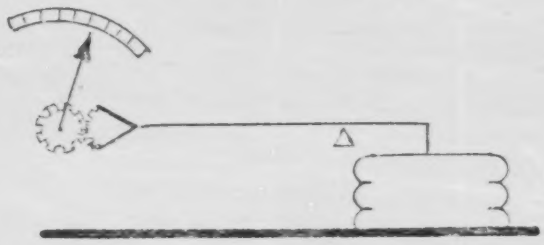


Fig 3. Aneroid barometer

The aneroid barometer consists of an evacuated can. A diaphram on one end moves as the pressure of the air on the outside changes. The movement of the diaphram is magnified by levers and transformed to movement of a pointer. The pressure is read on a dial. See figure 3.

Standard atmospheric pressure in various units are listed in Table 1. Notice that the height of a column of liquid is given in some cases. It is easier to simply state the height of a column of liquid than to use equation 2 to actually calculate the pressure. The height of the liquid and the name of the liquid make up what is known as the pressure head. The pressure head is the h in the formula $P = hD$.

1 atm
14.7 lb/in^2
30 in Hg
34 ft H_2O
76 cm Hg
10^5 N/m^2

Table 1
Atmospheric Pressure

PRESSURE SCALES

If a mercury barometer was placed inside a tall bell jar, the height of the column of mercury would decrease as the air is removed. If all the air is removed there would be no column of mercury and the pressure inside the bell jar would be zero. It would contain a perfect vacuum. A barometer measures pressure on an absolute scale. There are no negative readings on an absolute scale since the zero is at the lowest possible pressure. In fact, there is no pressure at the zero reading.

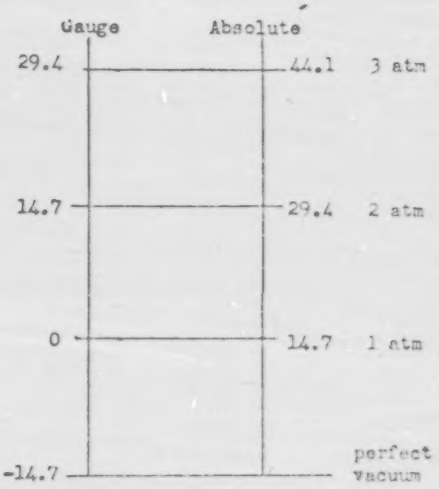


Fig 4. Pressure scales (lb/in^2)

Other pressure measuring devices, also, measure pressure on an absolute scale. However, some pressure gauges read the excess of pressure over that of the atmosphere. On this scale the gauge would read zero when it is open to the atmosphere. Pressures on such gauges read pressure on a gauge scale. The markings on the scales in figure 4 are in pounds per square inch. Naturally, the units could be any pressure or pressure head units. Some gauges may even mix units. They may read pounds per square inch above zero and inches of mercury below zero, for example. The markings below zero on the gauge scale are negative pressures or units of vacuum. Notice that conversion to absolute scales are accomplished by adding one atmosphere of pressure (in appropriate units) to the gauge value:

$$P_A = P_G + 1 \text{ atm} \qquad 3.$$

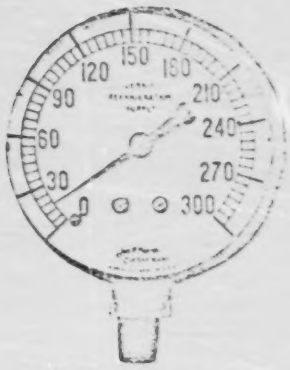
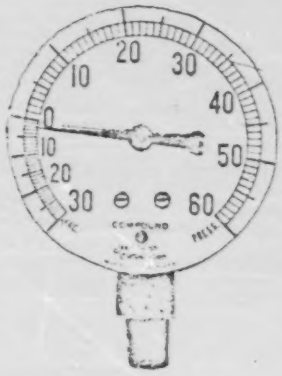


Fig 5 (a) Absolute pressure (lb/in^2)



(b) gauge pressure
Press (lb/in^2) vac (in Hg)

PRESSURE MEASURING DEVICES

A simple device for measuring pressure head is the manometer. It is used for measuring relatively small gas pressures. It consists of a U-shaped tube (see figure 6) filled with liquid (usually oil, water or mercury). The pressure is applied to the tube, forcing the liquid down on that side and up on the other. The difference in levels is the pressure head. Equation 2 can be used to calculate the pressure if needed.

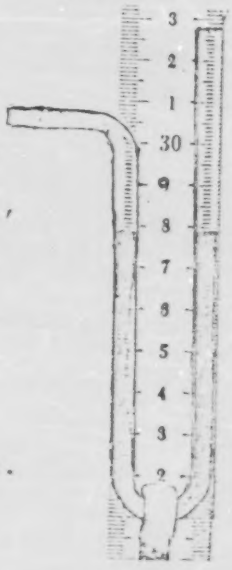


Fig 6 Manometer

Fig 7 Bourdon gauge

Manometers filled with oils or water are extremely sensitive measuring instruments. Pressure changes of 0.001 lb/in^2 or less are easily distinguished.

Bourdon gauges consist of a sealed tube that is bent into a C, helical, spiral or twisted shape. When pressure is applied, internally, the tube tends to straighten. Motion at one end of the tube is magnified by levers and transformed to rotational movement of a pointer. The pressure is read on a calibrated scale. Figure 7 shows a C-shaped Bourdon gauge.

ARCHIMEDES' PRINCIPLE

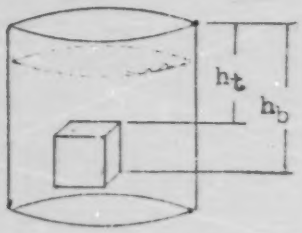


Fig 8 Submerged cube

When an object is submerged in a fluid, the upward force on the bottom due to fluid pressure is greater than the downward force on the top. This is always true because of the greater pressure at greater depths. The shape of the object makes no difference.

Figure 7 shows a submerged cube with its top and bottom horizontal. The net force on the object due to liquid pressure is the upward force on the bottom (F_B) minus the downward force on the top (F_T). The net force is called the bouyancy ($B = F_B - F_T$). Since force is pressure times area the formula becomes: $B = P_BA - P_TA$. Substituting equation 2, it becomes $B = Dh_BA - Dh_TA$ or $B = DA(h_B - h_T)$. The quantity $h_B - h_T$ is the height of the cube so $B = DAh$ The product Ah is the volume of the cube, therefore:

$$B = (D_{\text{fluid}})(V_{\text{object}}) \qquad 4.$$

Since density times volume is weight, the bouyancy must be the weight of something. The density of the fluid times the volume of the object is the weight of an equal volume of fluid or simply the weight of the fluid displaced by the object.

Equation 4 is a statement of Archimedes' principle. Note that it is not a fundamental law of nature since it is derived from various definitions and formulas. It is, perhaps, easier to understand when written in words:

> Archimedes' Principle: When an object is placed in a fluid, it is bouyed up by a force equal to the weight of the displaced fluid.

This statement applies to any shaped objects whether it is completely submerged or not. It is best to keep the following in mind, however:

> Submerged objects: An object that is completely submerged displaces its own volume of the fluid in which it is submerged.
>
> Floating objects: A floating object sinks to a point where it just displaces its own weight of the fluid in which it is floating.

Bouyant forces can be measured by finding the difference between an objects weight in air and its weight when submerged completely. The bouyant force on a floating object equals the weight of the object in air.

SPECIFIC GRAVITY

When a person says "aluminum is lighter than steel", what does he mean? Certainly, 100 lb of aluminum is not lighter than 50 lb of steel. What is really meant by the statement is the density of aluminum is less than the density of steel. Comparisons of this kind have the unspoken intent of comparing the weight of equal volumes of different materials.

Specific gravity is a quantity that makes such a comparison:

$$\text{Sp gr} = \frac{Ds}{Dw} \qquad 5.$$

Where Ds is the density of the substance and Dw is the density of water. Notice that specific gravity has no units. The specific gravity of mercury is 13.6, for example. This means it is 13.6 times more dense than water. You should memorize the density of water in several units. See Table 2.

62.4 lb/ft^3
0.036 lb/in^3
8.33 lb/gal
1 g/cm^3
1000 kg/m^3
1 kg/ℓ

Table 2
Density of Water

The specific gravity of a solid material can be found by weighing the object in air; then in water. The difference or loss of weight is the weight of an equal volume of water so the specific gravity is:

$$\text{Sp gr} = \frac{\text{weight in air}}{\text{loss of weight in water}} \qquad 6.$$

Hydrometers are used to measure the specific gravity of liquids. It is usually a sealed glass tube which encloses a scale and is weighted on one end. It is a floating object so it sinks until it displaces its own weight. The specitic gravity is read on the scale right at the surface of the liquid in which it floats. In "lighter" liquids it must sink deeper to displace its own weight than in "heavier" liquids.

PASCAL'S LAW

Pascal's law was discussed in module M 9 (Simple Machines). It is repeated here for convenience.

> Pascal's law: When changes in externally applied pressures occur at one point in a confined fluid, the pressure will change by an equal amount at every other point within the fluid.

Additional information about Pascal's law is included in your textbook.

PROBLEMS

Module P 2 FLUIDS I (STATICS)

1. If one substance has a higher density than another, does this necessarily mean that the molecules of the high-density material are more densely packed? Explain.

2. Does a hydrometer that measures specific gravity of liquids that are more dense than water have the 1 at the top or bottom of the scale? Explain.

3. Distinguish between force and pressure. What are the units of each in mks, cgs, and British measuring systems.

4. Describe how each of the following measuring devices work and that quantity they measure: (a) Bourdon gauge, (b) hydrometer, (c) manometer and (d) barometer.

5. When an object is submerged, does the bouyancy depend on how far below the surface the object is? When an object is floating (such as a boat) does the depth of the water make any difference?

6. If a good vacuum pump is connected to a 2 m length of glass tube with a rubber hose and the lower end of the tube is dipped in an open container of mercury, how far up the tube will the mercury rise? Explain what causes the mercury to rise in the tube. Your explanation should account for the fact that the mercury would not rise in the tube at all if the experiment is performed in a place where there is no atmosphere. What would happen if the tube ran through a rubber stopper and into a sealed container of mercury? Assume very little air space.

7. Explain what is meant by each of the following terms: (a) standard atmospheric pressure, (b) a pressure of 25 atmospheres, (c) 20 in of vacuum, (d) water head, (e) gauge pressure, (f) atmospheric pressure of 30.11 in Hg (reduced to sea level).

8. Gasoline has a density of 5.66 lb/gal. What is its density in kilograms per liter? What is its specific gravity?

9. A certain grade of diesel fuel has a specific gravity of 0.85. What is its density in pounds per gallon? In kilograms per liter?

10. Ethylene glycol has a density of 1.105 kg/ℓ. When mixed 50/50 by volume with water (freezing point -40°F, its density is 1.053 kg/ℓ. What is the density in pounds per gallon in each case? What is the specific gravity in each case?

11. A car battery is fully charged when the specific gravity of the electrolyte is 1.250 and discharged when it is 1.100. Find the density in each case in pounds per gallon and kilograms per liter. Does the hydrometer float higher or lower in the electrolyte of a charged battery compared to one that discharged?

12. Diesel fuel pumps transmit fuel to the injector against pressures as high a 6000 lb/in^2. How many atmospheres of pressure is this?

13. The fuel pump on an automobile works against pressures of 3.5 lb/ (gauge) on the pressure side and 4.9 lb/in^2 of vacuum on the inlet side. Express these pressures in inches of mercury. What are these pressures on an absolute scale?

14. Intake manifold vacuums are (a) idling: 19 in Hg, (b) throttle suddenly opened: 5 in Hg, (c) throttle suddenly closed: 25 in Hg. Express each of these in pounds per square inch on an absolute scale and in centimeters of mercury on a gauge scale.

15. Tire pressure is 30 lb/in^2. How many atmospheres of pressure (absolute) is this?

16. A power steering pump on an automobile works against pressures of about 1000 lb/in^2. How many atmospheres of pressure (absolute) is this?

17. An irrigation pump driven by a diesel engine must work against about 60 lb/in^2 at ground level. What is the equivalent water head? If the well is 150 ft deep, how much pressure must the pump provide?

18. A small block of lead weighs 4.45 lb. When it is suspended in water it appears to weigh 4.06 lb. What is the specific gravity of lead?

19. During hard braking, a force of 100 lbs is applied to the brake pedal on a car. If the theoretical mechanical advantage of the brake lever is 7.5, what force is applied to the master cylinder piston? If the piston has a 1 in diameter, what pressure is created in the hydraulic circuit?

20. A power assist on a brake system consists of a cylinder 20 cm in diameter. One side of the piston is open to atmospheric pressure; the other to intake manifold vacuum when the brake is applied. If atmospheric pressure is 73 cm Hg (Eastern Nebraska elevation: 1200 ft) and the manifold pressure head is 13 cm Hg (absolute) find the force on the piston tending to push it to the right as shown in the diagram. If the end of the piston shaft at A is a hydraulic piston with a diameter of 1.2 cm, what pressure is created in the hydraulic circuit.

21. If the brake in problem 19 is applied as described so the pressure in the hydraulic circuit is 955 lb/in^2, what is the force applied on a rear wheel cylinder with a diameter of 15/16 in? What is the force on a front wheel cylinder with a diameter of 17/16 in?

ANSWER KEY (PROBLEMS)

Module P 2 FLUIDS I (STATICS)

1. No, molecules may be heavier.

2. Top, hydrometer sinks less in dense liquids to displace its own weight.

3. Pressure is force per unit area; N, N/m^2; dyne, $dyne/cm^2$; lb, lb/ft^2.

4. (a) pressure, (b) specific gravity, (c) pressure head, (d) atmospheric pressure head

5. No, no.

6. About 76 cm, atmospheric pressure on mercury in open container pushes mercury up the tube into regions of low pressure until the weight of mercury in the tube balances the force of the atmosphere.

7. (a) Average pressure at sea level, 45° latitude and at 15°C (average temperature of earth), (b) 25 times atmospheric pressure, (c) 20 in Hg less than atmospheric (vacuum pressures are gauge pressures), (d) length of column of water that a given pressure will support or pressure in a stand-pipe, (e) pressure scale with the zero at standard atmospheric pressure, (f) station pressure plus pressure due to a vertical column from station to sea level.

8. 0.679 g/ℓ, 0.679

9. 7.1, 0.85 kg/ℓ

10. 9.2 lb/gal, 8.77 lb/gal, 1.105, 1.053

11. 10.4 lb/gal, 9.2 lb/gal, 1.25 kg/ℓ, 1.1 kg/ℓ, higher

12. 408 atm

13. 7.1 kn Hg, -10 in Hg, 37.1 in Hg, 20 in Hg, (18.2 lb/in^2, 9.8 lb/in^2)

14. (a) 5.4 lb/in^2, -48.3 cm Hg
(b) 12.3 lb/in^2, -12.7 cm Hg
(c) 2.45 lb/in^2, -63.5 cm Hg

15. 3.04

16. 69

17. 139 ft H_2O, 124 lb/in^2 (gauge)

18. 11.4

19. 750 lb, 955 lb/in^2

20. 2510 N, 2.22 x 10 N/m^2 (564 lb, 3220 lb/in^2)

21. 660 lb, 750 lb

EXPERIMENTS

Module P 2 FLUIDS I (STATICS)

PURPOSE: The purpose of these experiments is (1) to study bouyancy of objects submerged in liquids, calculate the specific gravity of various solids and liquids and check the specific gravity of an unknown liquid using the hydrometer; (2) to study pressure in a balloon by measuring it with a manometer and plot a hysteresis curve (pressure-volume) as the balloon is inflated and then deflated.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.

2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.

3. Observe all cautions listed in the procedure section of these instructions.

EXPERIMENT I SPECIFIC GRAVITY

INFORMATION: Specific gravity is defined by equation 5 in the Information Sheets of this booklet:

$$\text{Sp gr} = \frac{Ds}{Dw} \qquad 5.$$

Where Ds is the density of the substance and Dw is the density of water. Specific gravity can also be found by dividing the weight of any sized sample of the substance by the weight of an equal volume of water.

When an object is submerged in water, the bouyancy is equal to the weight of an equal volume of water which is also equal to its loss of weight in water. So the specific gravity of a solid object can be found by equation 6:

$$\text{Sp gr of solid} = \frac{\text{weight in air}}{\text{loss of weight in water}}$$

The specific gravity of an unknown liquid can be found by submerging an object both in the liquid and in water, its specific gravity is:

$$\text{Sp gr of liquids} = \frac{\text{loss of weight in liquid}}{\text{loss of weight in water}}$$

Specific gravity or density tables can be found in your textbook on the pages given below. Recall that specific gravity is numerically equal to the density in grams per cubic centimeter. If the density is given in kilograms per cubic meter, move the decimal three places to the left. If it is given in pounds per cubic foot, divide by 62.4.

Introductory Applied Physics:	page 241
Elements of Physics:	page 157
Physics for Career Education:	page 190
Physics for Technology;	page 59
Modern Technical Physics:	page 198 - 199

EQUIPMENT:

1. Harvard trip balance mounted on stand
2. Light string or thread
3. Three specific gravity specimens (Sargent-Welch #1158)
4. Two beakers (600 ml)
5. Cylinder
6. Quantity of unknown liquid
7. Hydrometer (Sargent-Welch #5-42035-C)

Check to see that all the equipment is available before you start. Ask your instructor if you have any questions about it. Obtain a data sheet from the instructor.

NOTE: The hydrometer is very fragile and is stored separate from the rest of the equipment. When you are ready to use it (step 14) the instructor will get it for you.

PROCEDURE:

1. Mount the Harvard trip balance on the stand. See the accompanying figure. NOTE: A shorter stand with a tripod base is used.

2. Make a loop from the light string or thread (about 6 in diameter). Attach the loop to the hook on the underside of the balance.

3. Fill one beaker with water; the other beaker with the unknown liquid. Fill them to about the 400 ml level.

4. Attach the aluminum specimen to the string and weigh it first in air, then submerged in water, then submerged in the unknown liquid. Record on the data sheet (table 1). NOTE: It is essential that the specimen be dry before each reading. Use paper towels.

5. Attach the brass specimen and repeat step 4.

The balance has a socket to permit supporting it on the upright rod. A small hook extends below the base under the balance pan.

By permission: Sargent-Welch Scientific Company

6. Attach the iron specimen and repeat step 4.

7. Calculate the loss of weight of each specimen in water and in the unknown liquid. Record in table 2 on the data sheet. Note that each line in table 2 is the weight of equal volumes of the metal, water and unknown liquids.

8. Calculate the specific gravity of each specimen and record in table 3 on the data sheet. (Use equation 6).

9. Look up the specific gravity for each metal in tables in your textbook and record in table 3.

10. Calculate the error between the calculated value and table values for each metal.

11. Calculate the specific gravity of the unknown liquid and record in table 4 on the data sheet. (Use equation 7).

12. Calculate the average specific gravity for the three values in table 4.

13. Fill the cylinder with the unknown liquid (5 cm from top).

14. Obtain a hydrometer from the instructor and use it to measure the specific gravity of the unknown liquid. CAUTION: Use the hydrometer with care. It is very fragile.

15. Calculate the error between the calculated average value and the hydrometer value of the specific gravity of the unknown liquid.

16. Clean up the beakers, cylinders and specimens. Return the hydrometer to the instructor. Use paper towels for clean-up. Put everything back in the proper drawer.

EXPERIMENT II THE MANOMETER

EQUIPMENT:

1. Balloon (new)
2. Two manometers (water and mercury)
3. Shut-off valve
4. Rubber band
5. One-half meter stick

CAUTION: Do not inflate the balloon except as described below. The rubber will stretch and your readings will not show a hysteresis curve.

PROCEDURE:

1. Attach the balloon securely to the valve with a rubber band.

2. Atach a clean sterilized mouthpiece to the other end of the valve.

CAUTION: Only one person should inflate the balloon with the mouthpiece. They have been boiled to prevent the spread of germs.

3. Inflate the balloon through the valve to a diameter of about three inches. Do not inflate too much, then deflate. One person can measure as the other inflates the balloon. NOTE: Measure the balloon along its greatest diameter.

4. Attach the balloon to the water manometer: Lightly pinch the hose and attach. Move the hose back and forth until the manometer levels are equal.

CAUTION: Do not pinch the balloon when it is attached to the manometer. The pressure will blow the water out of the tube. If you should lose any of the water, call the instructor to refill.

5. Open the valve and record the difference in levels of the water in the manometer. At the same time, record the diameter of the balloon.

6. Remove the apparatus from the manometer and inflate the balloon to about 5 in (largest diameter). Reattach it to the water manometer, open the valve, read and record the difference in levels and the diameter.

7. Repeat step 6 several times for balloon diameters of about 7 in, 9 in and 11 in. Do not exeed 11 in (largest diameter) or the balloon will pop.

8. Repeat step 6 several times (except deflate the balloon) for diameters of about 9 in, 7 in, 5 in and 3 in.

9. Reinflate the balloon to about a 6 in diameter. Record the pressure head (water).

10. Calculate the pressure in dynes/cm^2. $P = (980\ cm/sec^2)(1\ g/cm^2)h$.

11. Using the pressure calculated in step 10, calculate the pressure head for a mercury manometer. See tables in your textbook for density.

12. Transfer the balloon to the mercury manometer and record the difference in levels.

13. Compare calculated and measured mercury pressure heads.

14. Plot a graph of the data obtained in steps 6 through 8 to obtain a hysteresis curve. Plot pressure vs diameter.

15. Question: Does the manometer read absolute or gauge pressure? Explain.

16. Use paper towels to clean up if necessary and put everything away in the proper drawer.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: P 3

Title: FLUIDS II (DYNAMICS)

Module Contents:
1. Rate of flow
2. Velocity of flow
3. Bernoulli's principle
4. Viscosity
5. Hydraulic valves and circuits

Program: This module has been prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to continue the study of the principles of hydraulics. These principles are used in fuel, lubrication, cooling, braking, steering and in numerous other kinds of power equipment in the automotive and diesel industries. This module also serves as an introduction to courses in fluid power.

Producer: Gene Waring

Date Produced: January 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 Part C, Research.

STUDENT INSTRUCTIONS

Module P 3 FLUIDS II (DYNAMICS)

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define rate of flow (volumetric).
2. State a formula for rate of flow in terms of the velocity of flow.
3. Define pressure head, velocity head and friction head and relate these quantities to the total head.
4. State the formula for velocity head.
5. Distinguish between streamline and turbulant flow.
6. State Bernoulli's principle in words only in terms of high and low velocities and high and low pressure.

7. Describe a venturi meter and use one to measure the rate of flow of liquids (or gases) through it.
8. Describe how a siphon works.
9. Describe various applications of Bernoulli's principle.
10. Describe how needle, check, pressure relief, sequencing and directional control valves work.
11. Use the DIGIAC 844 training console to set up various hydraulic circuits to investigate the function of the valves in objective 11, given a circuit diagram.
12. Solve various problems using the definitions and formulas in objectives 1, 2, 3 and 4.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of fluid dynamics. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this book-

let (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbooks plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N. C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 11, sections 11.13-11.21, pages 282-295 and chapter 12, sections 12.21, pages 314-316.

C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 13, sections 13.1-13.5, pages 167-173.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden. L., Prentice-Hall Inc., 1st ed., 1974. This text does not include the subject of fluid dynamics. See Information Sheets (A).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 13, sections 13.8-13.10, pages 202-212.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 14, sections 14.5-14.6, pages 220-225.

II. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving fluid dynamics problems. The problems from number five on are applied to your technology.

III. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

IV. Performing Laboratory Experiments: There are two experiments in this module. They will give you practice in learning about fluid dynamics and hydraulic circuits. Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (P 3) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of furtner study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module P 3 FLUIDS II (DYNAMICS)

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Total head = pressure head + velocity head + friction head.

T - F 2. The velocity of flow out of a hole in the bottom of a tank depends on the size (area) of the hole.

T - F 3. Eddy currents are found in streamline flow only.

T - F 4. A check valve is one in which flow is allowed to proceed one direction only.

T - F 5. Fluids always moves from regions of high pressure to regions of low pressure.

6. Fluid flows at a rate of 2.5 ℓ/s in a pipe of 1.5 cm diameter. Its velocity in meters per second is:

a) 44.2 c) 22.6

b) 14.1 d) 1.67

7. If the rate of flow of air in a duct is 800 ft^3/min, how many cubic feet will pass a point in 3.5 hr?

a) 230 c) 168 000

b) 2800 d) 16 800

8. If 5000 gal of gasoline can be unloaded from a transport truck in 29 min and the unloading pipe is 3 in in diameter what is the average velocity of the gasoline in the pipe? (1 gal = 231 in^3).

ANSWER KEY TO THE SELF-EVALUATION TEST

Module P 3 FLUIDS II (DYNAMICS)

Question-Answer	If you missed this question, you are directed to these learning activities
1. T	I Reading or III Problems
2. F	I Reading
3. T	I Reading
4. T	V Experiment #2
5. F	I Reading or V Experiment #1
6. b	III Problems
7. c	III Problems
8. 7.8 ft/s	III Problems

INFORMATION SHEET

Module P 3 FLUIDS II (DYNAMICS)

When a faucet is turned on in the home, water begins to move. It may be moving at a relatively high speed at the faucet and in the pipes leading to it. Back in the large underground mains, however, the change in speed may be barely noticable. Even so, there is an enormous amount of water that has begun to move, from the faucet all the way back to the stand-pipe or pumps. Water in pipes that may be several miles long must start moving. Pressure exerted by the pump or by the liquid column in the stand-pipe must provide the force necessary to accelerate the water.

NOTE: If the rate of flow is 5 gal/min, water will move at about 3.4 ft/min in 6 in mains. About 6.5 tons of water will be moving at this speed for each mile of 6 in main back to the pumping station.

Turning the faucet off creates a problem, also. Tons of moving water must be stopped. To prevent the pipes from "banging", an impact absorbing device must be installed. This is an air chamber into which the flow can be diverted to absorb the flow energy.

As you can see the inertia of fluids plays and important part in fluid dynamics. Friction, also, plays an important role in the flow of liquids and gases in pipes, ducts and other conduits. Friction depends on the size of the pipe, the smoothness of the inner surface of the pipe, the number of bends and turns the pipe makes, and the resistance to flow of the fluid itself.

The property of fluids that tend to resist flow is called viscosity. The layer of molecules touching the inner surface of a pipe will adhere to it. These molecules do not move. The next layer sticks to the first layer by cohesive forces. A few molecules in the second layer slip past those in the first. There is more movement in the third layer and even more in the fourth. This continues to the center of the pipe where the fluid is moving at its fastest speed.

If the molecules of a liquid have a strong cohesion for each other, there will be a strong resistance to flow and they have a high viscosity. "Heavy" oils are examples of high viscosity liquids. The viscosity of a given liquid will increase as temperature decreases. Viscosity is important in lubrication and in cross-country oil and gas pipelines.

If the velocity of flow becomes too great, eddy currents will form and the flow becomes turbulant. The amount of friction is increased in turbulant flow as compared to streamline flow. A molecule moves past a certain point and then follows a certain path from then on. If the flow is streamline, all other molecules that pass through the same point will follow exactly the same path as the first one. This does not happen in turbulant flow.

RATE OF FLOW

The volumetric rate of flow (Q) must be distinguished from the speed

of flow. In a given pipe the rate of flow must be constant. This is true since there is no place for the fluids to pile up. In figure 1, if 5 gal flow past point a in 1 min, then 5 gal must flow past point b in 1 min.

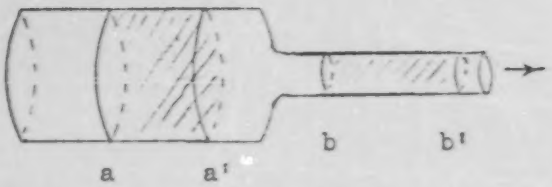


Fig 1. Liquid flow in a pipe

The rate of flow is defined by the formula:

$$Q = \frac{V}{t} \qquad 1.$$

Where V is the volume flowing past a given point in time t. Its common units are gal/min, ft^3/s, ℓ/s, m^3/s, acre-ft/hr, etc.

Suppose and imaginary cross-section at point a in figure 1 moves to point a'. The cylinder of liquid between the points has a volume $V_a = A_a s_a$ where A_a is the cross-sectional area at point a and s_a is the distance between a and a'. The rate of flow from equation 1 becomes: $Q = A_a s_a / t$. The quantity s_a/t is the speed of flow (v_a). So equation 1 becomes:

$$Q = Av \qquad 2.$$

Since the rate of flow at point a must equal the rate of flow at point b, then:

$$A_a v_a = A_b v_b \qquad 3.$$

Since A_b is smaller than A_a, then v_b must be larger than v_a for the products to be equal. Note that the speed of flow is greater in smaller pipes but the rate of flow is the same.

BERNOULLI'S PRINCIPLE

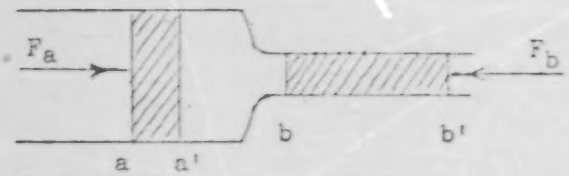


Fig 2.Bernoulli's principle

If the law of conservation of energy (work equation) (see module M 8) is applied to the liquid in the pipe of figure 2, the equation becomes:

$$\tfrac{1}{2}m v_b^2 - \tfrac{1}{2}m v_a^2 = (F_b - F_a)s$$

m is the mass of water between a and a' or b and b'. F_a is the force on the mass of water at a and F_b is the force on the mass at point b'. If this equation is rearranged and each term devided by the volume of water in each section it becomes:

$$P_a + \tfrac{1}{2}dv_a^2 = P_b + \tfrac{1}{2}dv_b^2 \qquad 4.$$

Where P is the pressure, d is the density and v is the velocity. The second term on each side of the equal sign is the kinetic energy per unit volume (ft lb/ft^3, J/m^3 etc.). It has the same units as pressure (lb/ft^2, N/m^2, etc.).

Notice that v_b is greater thatn v_a. This means that P_b must be less than P_a for the two terms on both sides to have the same sum. Equation 4 is Bernoulli's principle and is derived from the work equation. In words it is:

> Bernoulli's principle: In streamline flow of fluids in pipes or ducts, at points where the velocity is high the pressure is low, and at points where the velocity is low the pressure is high.

Equation 4 would have to include the gravitational potential energy per unit volume on each side if the vertical levels of points a and b were different. Bernoulli's principle is true only if there is no loss of pressure due to friction between the two points.

PRESSURE HEAD

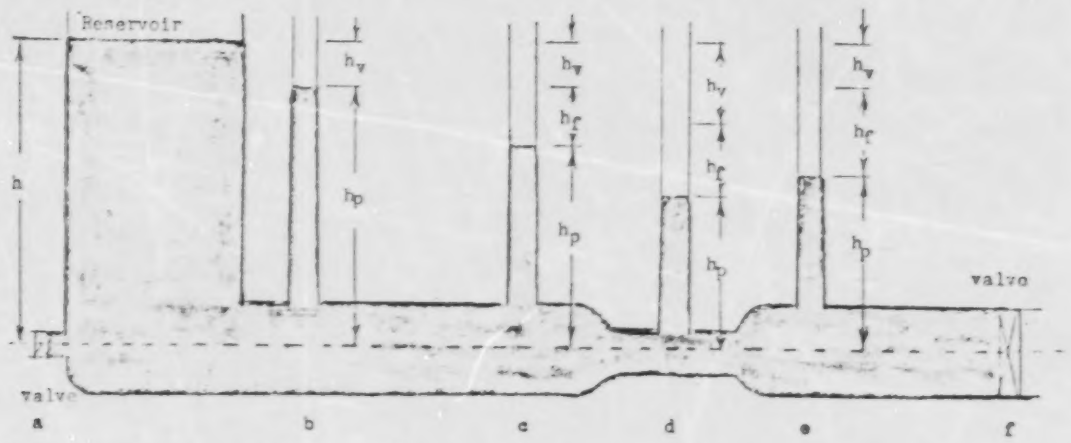


Fig 3. Velocity head + friction head + pressure head = total head.

The water level in the reservoir in figure 3 is maintained with a total pressure head h. Valves are located at points a and f. If both valves are closed the level of the water in manometer tubes b,c,d,and e will be the same as in the reservoir. If valve a is opened, water runs out. The speed (v) of the stream at the valve is given by the formula:

$$v = \sqrt{2gh} \qquad 5.$$

Where g is the acceleration of gravity. The velocity of the stream is called the velocity of efflux. This formula is derived from a more complex form of Bernoulli's principle (equation 4).

Example: If the reservoir level is 100 ft above the valve at a, find the velocity of efflux at the valve. If the open

valve forms a circular opening with a ½ in radius, find the rate of flow.

Given: $h = 100$ ft
$g = 32$ ft/s^2
$r = 0.5$ in $= 0.0417$ ft

Solution: $v = \sqrt{2(32 \text{ ft/s}^2)(100 \text{ ft})} = 80$ ft/s
$Q = Av = (\pi r^2)v$ (equation 2)
$= \pi(0.0417 \text{ ft})^2 \cdot (80 \text{ ft/s})$
$= 0.436$ ft^3/s
$= 3.26$ gal/s

Example: How much water, in the previous example, will run out in 5 min?

Given: $Q = 3.26$ gal/s
$t = 5$ min $= 300$ s

Solution: $V = Qt$ (equation 1)
$= (3.26 \text{ gal/s})(300\text{s}) = 978$ gal

Note that if valve a was some distance away on the end of a pipe, the pressure head would be reduced because of friction. This would reduce both velocity and rate of flow.

Refer to figure 3 again. If valve a is closed and valve b is opened, the water levels in manometer tubes b,c,d and e change. Tube b is assumed to be close to the reservoir so there is no friction loss. However, Bernoulli's principle suggests there will be lower pressure because the water is moving at point b in the pipe. The pressure head (h_p) is lower than the total pressure head by an amount (h_v) called the velocity head. The velocity head can be calculated by equation 5 if the velocity is known.

$$h = \frac{v^2}{2g} \qquad 6.$$

Tube c shows the same velocity head loss as point b since the velocity of the water in the pipe is the same. Since tube c is further away from the reservoir, there is an additional loss of pressure due to friction called the friction head (h_f). Note that the total head equals the pressure head plus the velocity head plus the friction head:

$$h = h_p + h_v + h_f \qquad 7.$$

Tube d is in a narrow section of the pipe where the velocity is greater. Since the velocity head has increased the pressure head is less. At point e the velocity head has changed back to what is was at point c. The pressure head is less at e than at c because the friction head has increased with the distance from the reservoir.

Example: Find the pressure head at point e if the total head is 100 cm. The friction head is 72 cm and water is flowing at a rate of 1.2 ℓ/min. The tube has a 0.8 cm radius.

Given:
$p = 100$ cm
$p_f = 20$ cm
$Q = 1.2$ ℓ/min $= 20$ cm^3/s
$r = 0.8$ cm

Solution:
$v = Q/A = Q/\pi r^2$
$= (20 \text{ cm}^3/\text{s})/\pi(0.8 \text{ cm})^2$
$= 9.95$ cm/s
$h_v = v^2/2g = (9.95 \text{ cm/s})^2/2(980 \text{ cm/s}^2)$
$= 0.01$ cm
$h_p = h - h_v - h_f$
$= 100 \text{ cm} - 0.01 \text{ cm} - 72 \text{ cm} = 28 \text{ cm}$

Example: Find the pressure head at point d for the previous problem Assume the friction head is the same. The radius of the pipe at d is 0.4 cm.

Given:
$r = 0.4$ cm
$Q = 20$ cm^3/s

Solution:
$v = (20 \text{ cm}^3/\text{s})/ (0.4 \text{ cm})^2$
$= 39.8$ cm/s
$h_v = (39.8 \text{ cm/s})^2/2(980 \text{ cm/s}^2)$
$= 0.8$ cm/s
$h_p = 100 \text{ cm} - 0.8 \text{ cm} - 72 \text{ cm} = 27.2 \text{ cm}$

Notice that the pressure head differs by about 0.8 cm at points d and e and is less at point d.

VENTURI METER

The constriction at point d in figure 3 is known as a venturi. The throat of a carborator on an automobile is an example. When manometers (or pressure gauges) are located at points d and e the device is known as a venturi meter and can be used to measure the rate of flow of the fluid through it.

Using equation 6 to find the difference in the velocity head at the two points and substituting the ratio Q/A for v the equation formed becomes:

$$Q = A_d A_e \sqrt{\frac{2\Delta P}{A_e^2 - A_d^2}} \qquad 7.$$

Where Δh is the difference in velocity heads. If there is no change in friction head between the two points then Δh is also equal to the difference in pressure head which is the difference in levels of the manometers.

In tems of pressure units equation 7 is:

$$Q = A_d A_e \sqrt{\frac{2\Delta h}{d(A_e^2 - A_d^2)}} \qquad 7a.$$

Where ΔP is the pressure difference and d is the density of the fluid.

SIPHON

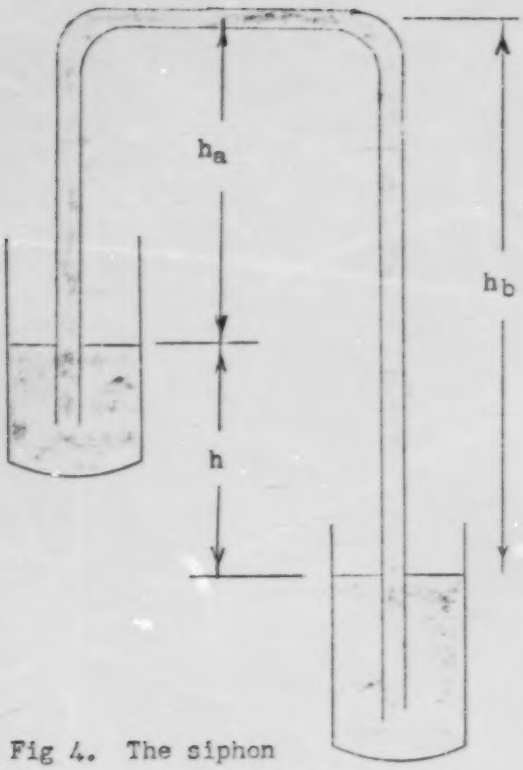


Fig 4. The siphon

The upper and lower basin in figure 4 are attached by a hose that acts as a siphon. The levels of liquid differ by a vertical distance h. If the distance h is not too great then h is the pressure head. Neglecting losses due to velocity and friction heads, the speed of flow is given by equation 5 and the rate of flow by equation 2. The distance from the level of the upper basin to the top of the siphon hose cannot exceed 34 ft since it is the atmospheric pressure that forces the water up the hose.

The force on the water in the hose at point A is one atmosphere minus Dh_A and at point B it is one atmosphere minus Dh_B. The force on the water in the hose is greater at the upper level than at the lower end. Fluids will always flow from an upper level to lower.

HYDRAULICS

Objectives 10 and 11 refer to various hydraulic valves and equipment and to the DIGIAC 844 training console. Information about this equipment is included in the technical manuals that accompany this equipment. It will be made available to you as you use this equipment.

PROBLEMS

Module P 3 FLUIDS II (DYNAMICS)

1. Describe streamline flow. Discuss the behavior of particles following a particular path.

2. How does turbulant flow differ from streamline (laminar) flow? What are eddy currents. How does speed of flow affect turbulance?

3. How is total head, pressure head, friction head and velocity head related? What are some of the things that friction head depends on?

4. Define viscosity. How does friction head depend on it?

5. How is Bernoulli's principle related to the law of conservation of energy? Does the principle hold in fluid flow in which turbulant flow is present?

6. If an automobile can get 15 mi/gal of gasoline at 60 mi/h, what is the average rate of flow of the gasoline in the fuel lines? What is the average velocity of the gasoline in quarter-inch copper tubing?

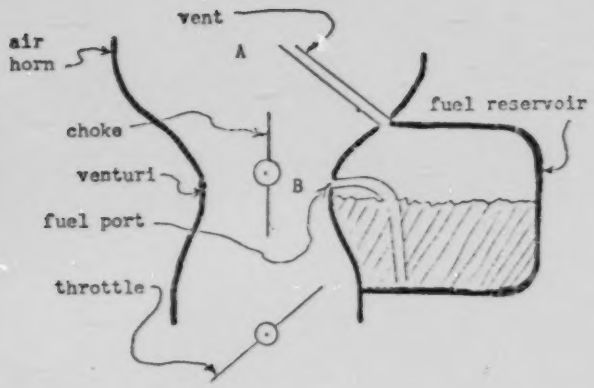
7. At 60 mi/h the water pump on a V-8 engine moves water at a rate of about 66 gal/min. What is this rate in liters per second? What is the velocity of flow through the 3.5 cm upper hose?

8. At an engine speed of 3000 rpm, the water pump must pump the coolant against a friction head of about 115 ft of water. What is the pressure loss due to friction in pounds per square inch? NOTE: Restrictions in the cooling system of an engine (radiator,hoses, thermostats and cooling jacket) create a lot of resistance to flow.

9. At an engine speed of 5000 rpm, the water pump on an automobile must work against a friction head of about 355 ft of water. Find the pressure loss due to friction in pounds per square inch. In newtons per square meter.

10. At an engine speed of 5000 rpm, the flow velocity of coolant in the 1.5 in upper hose is 7.6 ft/min. What is the flow rate in gallons per minute? In liters per second? What is velocity head in the upper hose?

11. At 60 mi/h, the rate of air flow through a carborator is about 80 ft^3/min in a 6-cylinder engine. The carborator is single-barreled and has a single venturi. The cross-sectional



area at the top of the air horn (point A) is 3.45 in^2 (2.25 in diameter minus cross-section of vent pipe). The cross-sectional area of the venturi (point B) is 0.91 in^2 (1.25 in diameter minus cross-section of choke shaft). What is the speed of the air at these two points?

12. If the speed of the air passing through the carborator in problem 11 is 55.7 ft/s at point A and 211 ft/s at point B, find the difference in pressure between the two points. The weight density of air is 0.0755 lb/ft^3. Assume the air does not compress or expand and no friction head exists between the two points. Hint: Solve equation 4 to get $P_a - P_b = \frac{1}{2}d(v_b^2 - v_a^2)$. Express the difference in pressure in inches of mercury and inches of water.

INFORMATION: The pressure at point A is greater than that at point B. Since the gasoline reservoir on the carborator is vented to point A, the higher pressure in the reservoir will push the gasoline up the tube leading to the fuel port. Although the pressure could force the gasoline to a greater vertical height, it is only necessary to push it an inch or so for it to dribble out into the venturi section of the air stream. Here the gasoline is atomized. That is; the gasoline breaks up into a spray of very fine mist. In a mist form the gasoline readily vaporizes in the warm manifold before entering the cylinder.

Evaporation causes the air-vapor mixture to cool and become more dense. Thus, a greater concentration of oxygen is pulled into the cylinder during the intake stroke. Greater amounts of oxygen provides a greater degree of combustion of the fuel. Diesel engines do not have this advantage and must draw cool air from some distance from the warm engine. Air is drawn from above the cab on a diesel truck for example.

13. If the pressure difference created by the venturi in problem 12 is 0.34 lb/in^2, to what vertical height could the gasoline be raised? The weight density of gasoline is 5.61 lb/gal.

14. An above-ground fuel storage tank is nearly full of diesel fuel. A hole 2 mm in diameter is located 2.4 m below the fuel level. What is the velocity of efflux and the rate of flow of the fuel spilling out of the hole? What volume will leak out in 10 min if the level doesn't change appreciably.

15. A diesel truck has an auxillary fuel tank for emergency use. It drains into the main tank by opening a shut-off valve in the line that connects them. What is the velocity of flow between the two tanks when the difference in levels in 20 cm? What is the rate of flow at this instant if the tubing is 0.95 cm in diameter? Note that tubing connecting the bottom of two tanks works the same as a siphon except a siphon would not work at all without atmospheric pressure acting on the liquids in the two tanks.

16. What is the pressure head in a hydraulic line in which the total head is 100 cm of mercury if the velocity head is 1.5 cm of Hg and the friction head is 37.4 cm of Hg?

ANSWER KEY

Module P 3 FLUIDS II (DYNAMICS)

1. All particles passing through a given point in streamline flow will follow the same path.

2. Swirls or eddy currents form in turbulant flow. Flow may be streamline at slow speeds; turbulant at higher speeds.

3. $h = h_p + h + h_f$, viscosity, inner surface of pipe, turns and bends in the pipe, speed of flow etc.

4. Friction head is greater in fluids of higher viscosity.

5. Bernoulli's principle is a special case of the law of conservation of energy. No.

6. 4 gal/h, 1.36 ft/min

7. 4.16 ℓ/s 104 cm/s

8. 49.7 lb/in^2

9. 153 lb/in^2, 1.06 x 10^6 N/m^2

10. 100 gal/min, 6.31 ℓ/s, 0.003 in H_2O

11. 55.7 ft/s and 211 ft/s

12. 0.34 lb/in^2, 0.69 in Hg, 9.44 in H_2O

13. 14 in

14. 7 m/s, 49.5 mℓ/s, 29.7ℓ

15. 198 cm/s, 140 mℓ/s

16. 61.1 cm Hg

EXPERIMENTS

Module P 3 FLUIDS II (DYNAMICS)

PURPOSE: The purpose of these experiments is (1) to study Bernoulli's principle as it applies to the flow of a liquid through a venturi tube and (2) to use the DIGIAC 844 training console to investigate the function of various valves and hydraulic circuits.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.

2. Never interfere with an experiment someone else is performing or with the equipment they are using.

3. Observe all cautions listed in the procedure section of these instructions.

EXPERIMENT I BERNOULLI'S PRINCIPLE

EQUIPMENT: Check to see if all the following equipment is available before you start. If you have any questions about it ask the instructor.

1. Mounted venturi tube with two manometer tubes
2. One constant level tank
3. Stand with tripod base (1 m long or more)
4. Hose
5. Sink for catch basin and drain
6. One 4 ℓ beaker
7. One 2 ℓ beaker
8. Timer
9. Caliper (vernier)

PROCEDURE: Obtain a data sheet from the instructor.

NOTE: Three students are required to perform this experiment. One student will pour water into the constant level tank. The second student will read the manometer and operate the timer. The third student will catch water as it flows out the end of the venturi tube.

CAUTION: Use care to avoid breakage of glassware.

1. Insert the rubber stopper with hose attachment to the left end of the venturi tube. The other rubber stopper goes in the right end pointed slightly downward. Water comes out the hole in the rubber stopper and into the sink.

2. Mount the constant level tank on the stand and connect it to the venturi tube with the rubber hose. The tank should be about 1 m above the tube.

3. Set the apparatus in a position so water coming out of the tube will flow into the sink.

4. Student #1 should fill the 4 ℓ beaker with water and practice pouring it into the tank. Try to maintain a constant level within an inch of the top. Once you begin don't allow the water to empty out of the tank. A new beginning will be required if air gets into the hose. (See next step.) If you run low of water, student #3 can fill it for you with the 2 ℓ beaker. Use care to avoid water spillage. Clean up with paper towels.

5. Once water begins to flow, student #2 should hold his fingers over the ends of the manometer tube and tilt the apparatus back so the air is revoved from the venturi and manometer tubes. Use care so the water continues to flow into the sink.

6. After the air is removed, student #3 should see that student #1 has at least 3 ℓ of water. If necessary pour some into his container.

7. Once constant level is maintained, student #3 should place his empty, dry beaker under the stream. At the same time student #2 should start the timer and record both manometer readings.

8. After about 2 ℓ of water has been caught by student #3, he should remove it from the stream. At the same time, student #2 should stop the clock. Student #1 may then stop pouring water into the tank.

9. Measure the water in the 2 ℓ beaker as accurately as you can. Record the volume and the time. These two quantities determine the rate of flow.

10. Use the vernier caliper to measure the inside diameter of the venturi tube at the right end. NOTE: The right and left ends have the same diameter so it is not necessary to dismantle the apparatus.

11. Calculate the area of the venturi tube at the right end.

12. Calculate the rate of flow. Use information from step 9.

13. When equation 7 (Information Sheet) is solved for A_b it becomes:

$$A_b = QA_a\sqrt{\frac{1}{Q^2 + 2g\Delta hA_a^2}}$$

Use this equation to solve for the cross-sectional area at the narrow part of the venturi tube. NOTE: Make sure all units are cgs: (Q-cm^3/s, A-cm^2, and g = 980 cm/s^2.

14. Use the formula for the area of a circle to determine the diameter of the narrow part of the venturi tube.

15. The measured diameter of the narrow section is 0.74 cm. At the point where the manometer tube is attached, there is a flare which increases the size of the tube where pressure is measured. The flare adds about 30% to the diameter of the tube (0.95 cm). Compare your calculated diameter (step 14) to this value.

16. Calculate the velocity of flow at points b and c.

17. Clean up all spilled water with paper towels. Return the equipment to the proper box or drawer.

EXPERIMENT II DIGIAC 844 TRAINER

EQUIPMENT:

1. DIGIAC 844 training console
2. Various quick-connect hoses, tees and valves
3. Procedure handbooks

PROCEDURE: Obtain a data sheet from the instructor and a procedure handbook, There are seven experiments. Each experiment is accompanied by a hydraulic circuit diagram and instructions (test procedure).

1. Set up the hydraulic circuit according to the circuit diagram.

CAUTION: BE SURE TEST CONSOLE IS TURNED OFF WHEN MAKING CONNECTIONS.

2. Investigate the circuit by following the test procedure step by step.

3. Write down your observations on the data sheet at each test procedure step.

4. The following is a list of the experiments you should perform. These experiments require about 50 min of time. Three students should work together, taking turns setting up and operating the hydraulic circuits.

    1. Pressure: Investigates how pressure is created.
    2. Flow: Investigates how flow is created by a pump.
    3. Check Valves: Investigates the function of check valves.
    4. Pressure Relief Valve: Studies the function of pressure relief valves.
    5. Pressure Sequencing Valve: Studies the function of pressure sequencing valves.
    6. Directional Control Valve: Studies the function of a directional control valve.
    7. Directional Control Valve: Studies the function of a 3-position closed-center directional control valve.

5. Use paper towels to clean up the oil after you are finished and put everything away.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: T 1

Title: TEMPERATURE AND THERMAL EXPANSION

Module Contents:
1. Temperature
2. Linear expansion (solids)
3. Volume expansion (solids, liquids and gases)

Program: This module was written especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to study temperature and some of the effects on matter when temperature is changed. The temperature of an object is the property that controls the transfer of heat energy and the size of the object. Both the transfer of heat and thermal expansion are important in automotive and diesel engines, transmissions and other devices with close fitting parts. This module is a prerequisite for the modules that follow.

Produced by: Gene Waring

Date Produced: February 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module T 1 TEMPERATURE AND THERMAL EXPANSION

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define thermal equilibrium and temperature.

2. Describe the Fahrenheit, Rankine, Celsius and Kelvin temperature scales and convert a given temperature from one to the other. Describe absolute and "gauge" scales.

3. State the formula for linear thermal expansion for solids and use the formula to solve various problems.

4. Define differential expansion and describe the expansion of bimetalic strips.

5. State the formulas for volume expansion for solids and liquids and solve various problems with it.

6. Describe the unusual expansion of water.

7. State the general gas law.

8. Define each of the following gas expansion processes: isothermal, isobaric, isochoric, adiabatic and the throttling process.

9. Solve various problems involving the expansion processes (objective 8) using the general gas law.

10. State the formula for resistance of a wire in terms of length cross-sectional area and resistivity and solve various problems with it. This objective is for electrical, electronics and electromechanical students only.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of thermal expansion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test

(under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks. Information about special applications may also, be presented in the problem set printed on ivory paper.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 13, pages 321-349.

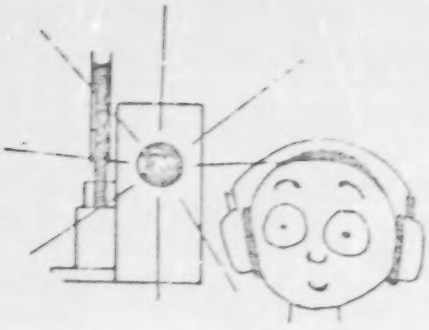
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 14, sections 14.4-14.5, pages 183-185 and chapter 15, sections 15.1-15.7, pages 195-200.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden. L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, sections 16.1-16.2, pages 208-212 and chapter 17, pages 220-228 and chapter 18, pages 229-234.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 14, section 1, pages 213-214, and chapter 15, sections 15.1-15.5 pages 235-250.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 17, section 17.1, pages 260-262 and chapter 18, sections 18.1-18.5, pages 274-282.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Heat Expands Metals (Doubleday Multimedia 13035).
B. Heat Expands Liquids (Doubleday Multimedia 13045).
C. Heat Expands Gases (Doubleday Multimedia 13055).
D. Gas Pressure and Temperature (Doubleday Multimedia 13245).
E. Heat Affects the Pressure of Gases (Doubleday Multimedia 13085).
F. Properties of a Gas (BFA-Laling 80-296).

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving thermal expansion problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about thermal expansion. Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (T 1) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

VI. Report: If you are an automotive or diesel student, complete the report on thermal expansion of a piston if your instructor requires it. Instructions are printed on salmon (orange) paper.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.).

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module T 1 TEMPERATURE AND THERMAL EXPANSION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Thermal equilibrium exists between two bodies when they contain the same amount of heat.

T - F 2. An isothermal expansion process is one in which temperature doesn't change.

T - F 3. Absolute zero may be thought of as the temperature at which distilled water freezes.

T - F 4. When a metal plate with a hole in it is heated, the diameter of the hole increases.

T - F 5. The density of most materials increases as the temperature increases.

Match the following (6,7 and 8):

_____	6.	Bathing suit	a) 308 K
_____	7.	Sweater	b) 10°C
_____	8.	Thermal underwear	c) 450°R

9. The temperature of an empty steel tank of 1000 gal capacity goes up in the hot sun by 80 C°. The coefficient of linear expansion for steel is 11 x 10^{-6}/C°. By how many gallons does the volume of the tank increase.

a) 2.64 gal c) 1.58 gal

b) 0.88 gal d) 0.11 gal

10. An oxygen tank has a volume of 2 ft^3 and a gauge pressure of 2200 lb/in^2. How many cubic feet of space would the oxygen occupy at atmospheric pressure (14.7 lb/in^2)? Assume an isothermal expansion.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 1 TEMPERATURE AND THERMAL EXPANSION

Question-Answer	If you missed this question, you are directed to these learning activities
1. F	I Reading
2. T	I Reading or III Solving Problems
3. F	I Reading
4. T	I Reading
5. F	I Reading or III Solving Problems
6. a	III Solving Problems
7. c	III Solving Problems
8. b	III Solving Problems
9. a	III Solving Problems or V Lab Experiment
10. 301 ft^3	III Solving Problems

INFORMATION SHEET

Module T 1 TEMPERATURE AND THERMAL EXPANSION

Thermometers are devices which have internal properties that change when the temperature changes. Solids, liquids and gases expand, electrical resistance changes, voltage across a thermocouple changes, colors change and other changes occur when temperature is changed. All of these properties are used in various types of thermometers.

When a thermometer is used (such as a mercury type), heat is exchanged between the material being tested and the thermometer until the temperature becomes constant. When this state is achieved, the thermometer and the substance are said to be in thermal equilibrium. Heat is no longer exchanged between the two objects and their temperatures are equal. When two objects are both in thermal equilibrium with a third object, they are in thermal equilibrium with each other.

Temperature is measured in Fahrenheit and Celsius degrees. These are the so-called gauge temperature scales since the zero is not at the bottom of the scale (similar to gauge pressure scales). The absolute pressure scales have zeros at the bottom of the scale and so do absolute temperature scales. The Kelvin scale has the same sized units as the Celsius scale. Rankine and Fahrenheit scales have the same sized units. Notice that between the freezing point and boiling point of water (see table 1) there are 180 degrees on the Fahrenheit and Rankine scales while on the Kelvin and Celsius, there are 100 degrees. This gives rise to the following conversion formulas:

Table 1. Temperature scales

$$\frac{F - 32}{9} = \frac{C}{5} \qquad 1$$

$$\frac{R}{9} = \frac{K}{5} \qquad 2$$

$$R = F + 460 \qquad 3$$

$$K = C + 273 \qquad 4$$

The ratio of 180/100 reduces to 9/5 in equations 1 and 2. Whenever a change in a quantity occurs due to a change in temperature then it is permissible to use "gauge" temperatures for solving problems. However, if a quantity depends on the actual temperature the absolute scales must be used. Note that the degree is not used with the Kelvin scale: 30°F, 65°C, 480°R but 300 K. Changes in temperature are indicated by putting the degree mark after the scale name: 25F°, 42C°, 800R° but 50 K.

THERMAL EXPANSIONS (SOLIDS)

The expansion of a rod, tape, rail, etc. depends on the original length, the material and the change in temperature.

$$\Delta L = \alpha L \Delta T \qquad 5$$

Where α is the coefficient of linear expansion. It is a property of matter (see table 2). Multiply by 5/9 to convert to 1/F°. Gaps are left in railroad rails and in the valve lift mechanism on an engine. Expansion joints are placed in concrete sidewalks and streets. Valve seat inserts can be installed by cooling them down and placing them in position. When thermal equilibrium is achieved, they will be set very tightly.

Material	α (1/C°)
Aluminum	0.000024
Bronze	0.000018
Copper	0.000017
Iron	0.000012
Steel	0.000011
Flint glass	0.000009
Pyrex glass	0.000003

Table 2. Coefficient of linear expansion

The circumference of a hoop or ring will increase when it is heated. This means the diameter also increases including that of the hole. A hole punched in a large plate will increase in size at the same rate as the plug that is punched out. As long as the plate and the plug are in thermal equilibrium, the plug will fit the hole. The diameter of the hole increases as the plate is heated.

A bimetalic strip is two lengths of metal fused together. When the temperature increases the strip will bend since one metal expands more than the other. This kind of expansion is called differential expansion. These are usually coiled and used in dial type thermometers or thermostats. The balance wheel of a watch is made of bimetalic materials.

AREA EXPANSION

When a square piece of sheet metal (length L and width L) is heated uniformly, it expands by ΔL in both directions. The original area is L^2 and the new area is $(L + \Delta L)^2$. If the expression for the new area is expanded it becomes:

$$(L + \Delta L)^2 = L^2 + 2L\Delta L + (\Delta L)^2 \qquad 6$$

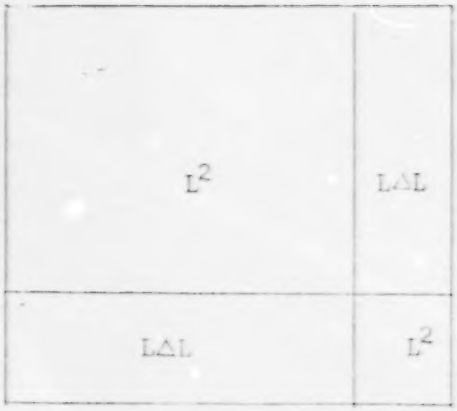


Fig 1. Area expansion

The terms of the expansion represent the areas shown in figure 1. If ΔL is small compared to L then $(\Delta L)^2$ will be a very small percentage of $2L\Delta L$ and can be ignored. If L is 10 cm, for example, the metal is steel and the temperature rise is 100°C, then ΔL equals 0.011 cm by equation 5. The middle term of equation 6 is 0.22 cm^2 and the last term is 0.000121 cm^2. The last term is only 0.055% of the middle term. So the middle term is considered as the entire increase in area. If equation 5 is substituted for ΔL in the middle term, the change in area becomes:

$$\Delta A = 2 \cdot A\Delta T \qquad 7$$

Where A is the original area.

VOLUME EXPANSION

If a cube (length L on each side) is heated, it expands by ΔL on each side. The new volume becomes $(L + \Delta L)^3$. If this expression is expanded and the small terms dropped the change in volume is:

$$\Delta V = 3 \cdot V\Delta T \qquad 8$$

Where V is the original volume. Notice that the volume coefficient for solids is three times the linear coefficient.

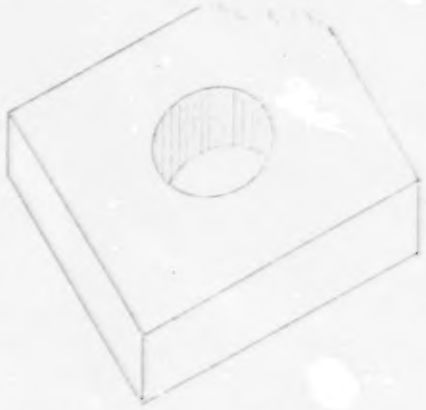


Fig 2. Expansion of a hole

A hole in a plate of metal expands both in diameter and thickness. If a thin sheet of metal was welded to the bottom, the hole would become a container. The change in volume of this little container can be calculated by using equation 8 if the temperature changes. The change in volume of the hole can be calculated just as if it were made of the same metal that surrounds it. The change in volume of any container (barrels, tanks, cans, bottles, etc.) can be obtained by using equation 8 and the correct coefficient of expansion.

EXPANSION OF LIQUIDS

Liquids expand the same way solids do but there is no listing of linear coefficients for liquids. The volume coefficients have been determined for a number of liquids (see table 3). The formula

for change in volume of liquids is:

$$\Delta V = \beta V \Delta T \qquad 9$$

Where β takes the place of 3α in equation 8. Do not multiply these numbers by 3.

Liquid	β (1/C°)
Alcohol (methyl)	0.00120
Gasoline	0.00105
Mercury	0.00018
Water (20°)	0.00037

Table 3. Volume coefficient of expansion

Notice that the volume coefficients of expansion for liquids are all larger numbers than the volume coefficients for solids. Aluminum has a volume coefficient of 72×10^{-6}/C° while mercury has a coefficient of 180×10^{-6}/C°. Any liquid will overflow its container when filled to the brim and allowed to warm up.

Example: A 100 gal steel tank is filled with 100 gal of gasoline. If the temperature increase in the afternoon is 25 C°, how much gasoline will overflow? NOTE: The differences in the expansion of the liquid and the tank determines the amount of overflow.

Given: $V = 100$ gal (tank and gasoline)
$\Delta T = 25$ C°
$\alpha = 11 \times 10^{-6}$/C° (steel)
$\beta = 105 \times 10^{-6}$/C° (gasoline)

Solution: $\Delta V = \beta V \Delta T$ (gasoline)
$= (105 \times 10^{-6}/C°)(100 \text{ gal})(25 C°) = 2.63$ gal
$\Delta V = 3\alpha V \Delta T$ (steel tank)
$= 3(11 \times 10^{-6}/C°)(100 \text{ gal})(25 C°) = 0.08$ gal
The overflow is 2.55 gal.

Example: By how much does the density of mercury change when the temperature increases by 100 C° if its original density at 0°C is 13.60 g/cm³. NOTE: The mass of a cubic centimeter will not change but its volume will.

Given: $d = 13.60$ g/cm³
$\Delta T = 100C°$
$\beta = 18 \times 10^{-6}/C°$
$V = 1$ cm³
$m = 13.6$ g

Solution: $\Delta V = \beta V \Delta T$
$= (18 \times 10^{-6}/C°)(1 \text{ cm}^3)(100 C°) = 0.018$ cm³
New volume equals 1.018 cm³
$d = m/v$
$= 13.60 \text{ g}/1.018 \text{ cm}^3$
$= 13.36$ g/cm³

Most materials expand when heated so the density decreases. Air rises when heated and sinks when cooled. Most fluids act the same way.

WATER

There are a few materials that expand when cooled in certain temperature ranges and expand when heated at other temperatures. At temperatures above $4^{\circ}C$ ($40^{\circ}F$) water expands when heated. Below $4^{\circ}C$ it expands when cooled. It expands also when it freezes. The less dense ice will flot on top of water. Water has its greatest density at $4^{\circ}C$.

EXPANSION OF GASES

The expansion of gases is complicated by the fact that pressure, amount of gas and volume may change when the temperature changes. In the study of the kinetic theory of gases in module P 4 an equation for the average kinetic energy of the molecules was developed:

$$1/2m\overline{v^2} = 3/2kT$$

Where m is the mass of the molecules, $\overline{v^2}$ is the average square of their velocity, k is Boltzman's constant and T is the absolute temperature. If both sides of the equation are multiplied by the number of moles of gas (n) and Avagadro's number (N_0), the equation becomes:

$$1/2M\overline{v^2} = 3/2nRT \qquad 10$$

Where M is the total mass of the gas (nN_0m) and R is the universal gas constant (kN_0).

When both sides of equation 10 are multiplied by two-thirds, both expressions are equal to the product of the pressure of the gas and its volume:

$$PV = 1/3nRT \qquad 11$$

This equation is known as the general gas law. If the n and T are transposed, the expression: PV/nT is seen to be a constant. Usually, the general gas law is written in this form:

$$\frac{P_1V_1}{n_1T_1} = \frac{P_2V_2}{n_2T_2} \qquad 12$$

Where subscript 1 denotes the initial conditions and subscript 2 indicates the conditions after a change has occured.

Equation 12 is usually written without the n's showing the relationship between pressure, volume and temperature when the amount of gas does not change:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad 13$$

In using this formula, remember to use absolute pressure and absolute temperature.

THERMODYNAMIC PROCESSES

Gases may undergo changes by five different "ideal" processes:

1. Isobaric process: An isobaric process takes place when a gas is heated in such a way that the pressure does not change. Water in a boiler of a steam engine, for example, is heated, vaporized and superheated all at a constant pressure. If the gas in a cylinder having a freely floating piston is heated, the temperature and volume increase without changes in pressure. Since P_1 and P_2 are equal in equation 13, they will drop out and the equation becomes:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \text{(Isobaric)} \qquad 14$$

This equation is known as Charles' law.

2. Isochoric process: An isochoric process takes place when a gas is heated at constant volume. The air or other gas in a sealed container undergoes an isochoric process when it is tossed into a trash fire. The pressure and temperature increase with practically no change in volume. It is an isochoric process up until the time the seam of the container splits and the can explodes (expands). Equation 13 becomes:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{(Isochoric)} \qquad 15$$

It is known as Gay-Lussac's law.

3. Isothermal process: The temperature remains constant in an isothermal process. A slowly advancing piston in a cylinder will compress the air in the cylinder isothermally. Remember that an advancing piston speeds up the molecules (and therefore the temperature) so the process must take place slowly to allow heat to flow out of the system.

$$P_1V_1 = P_2V_2 \quad \text{(Isothermal)} \qquad 16$$

This equation is known as Boyle's law.

Notice that in the first three processes, heat must flow into the system or out of it. Heat is not allowed to flow in either direction in the next two processes.

4. Adiabatic process: When no heat enters or leaves a system, the process is said to be adiabatic. The compression stroke on a gasoline or diesel engine is approximately adiabatic since it occurs so quickly (at 3000 rpm, the compression stroke takes 1/200 s) that there isn't time for much heat to be transferred.

   The explosion of gasoline occurs so rapidly (before the piston starts downward), the explosion is approximately isochoric. After the explosion the expansion that occurs on the downward power stroke is again adiabatic. On a diesel engine, the power stroke is not adiabatic since burning occurs almost throughout the power stroke with a lot of heat being added. Equation 13 applies to this process:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \text{(Adiabatic)} \qquad (13)$$ 17

5. Throttling process: When a fluid, originally at high pressure, passes through a narrow opening (such as a needle valve or an expansion valve) into a region of low pressure, the fluid undergoes an expansion known as the throttling process. In a mechanical refrigerator, fluid on the high pressure (and high temperature) side of the pump passes through the expansion valve as a continuous stream (liquid) into the low pressure side. There is no flow of heat between the high and low sides so the process is adiabatic. Formula 13 cannot be used since the liquid state is usually involved in the throttling process. The expansion is therefore much more complex involving changes in the internal energy of the fluid (attraction as well as kinetic).

Force is always present in thermodynamic process in the form of pressure. If motion takes place then, work will be accomplished. Note that work is done in all processes except isochoric. Changes in the internal energy of a gas occur in all processes in which a change in temperature occurs (all processes except isothermal). The flow of heat, changes in the internal energy and the work done in thermodynamic processes applied in the form of the law of conservation of energy forms the basis of the theory of heat engines and refrigeration devices.

Your textbook provides a number of example problems involving the gas laws.

PROBLEMS

Module T 1 TEMPERATURE AND THERMAL EXPANSION

1. What is the freezing and boiling points of water at normal atmospheric pressure on the Celsius and Fahrenheit scales? How many degrees is there between each point on the two scales? One Fahrenheit degree is how many Celcius degrees?

2. What determines whether an object feels warm or cool to the touch? Explain the transfer of heat between an object and your hand when the objects temperature is below 70°F, between 70°F and 98.6°F, at 98.6°F and above 98.6°F. When a book and a piece of metal are at 70°F, does one feel cooler than the other? Explain why.

3. When a mercury thermometer is placed in warm water, the mercury drops a little bit before rising. Explain why this happens. If it were placed in cold water would you expect it to rise a little before falling?

4. In the formula $\Delta L = \alpha L \Delta T$, does it matter whether the original or final length (L) is used?

5. What is an adiabatic process? If the ends of an unstretched rubber band are held with the center between your lips, then suddenly stretched, your lips will detect an increase in temperature. When the process is reversed, you will feel a decrease in temperature. Is this process adiabatic? Explain how the temperature of the rubber band changed.

6. Would you readily drink beer or a soft drink if its temperature was 277 K?

7. Would you willingly take a shower if the water temperature is 10°C?

8. During an illness, your temperature increased by 3.6 F°. Express this change on a Celsius thermometer.

9. Would you enjoy a pizza baked 20 min at 300°C and served with pepsi at 293 K?

10. Would you enjoy your favorite TV dinner if it had been baked for 30 min at 860 K and served with coke at 645°R?

11. The freezer compartment of a home refrigerator normally maintains a temperature of 0°F. At a temperature of 10°F or above, enzymes and other creepy-crawlies begin to cause food deterioration. If the actual temperature is 262 K, does the refrigerator likely need defrosting?

12. To conserve fuel, we have recently been asked to lower thermostats to 525°R. What is the recommended setting in degree Celsius?

13. If you wake up with a fever of 40°C, should you remain in bed?

14. Normal operating temperature of an engine is 780°F. What would the temperature gauge (Celsius) read on a European sports car?

15. When heating a piece of iron, it will begin to glow red at about 1000°F (noticeable in the dark). Give the equivalent Celsius temperature.

16. An aerosol spray can of starting fluid (ether) is not to be stored at a temperature higher than 130°F. Would a room where the temperature is never over 325 K be alright?

17. A valve lifter, pushrod and valve have a total length of 18 in. How much extra clearance should be allowed during assembly (temperature of 23°C) before makeing the final adjustments at normal operating temperature of 97°C? Assume all parts are steel with a coefficient of linear expansion of $11 \times 10^{-6}/C°$.

18. A micrometer is accurate if it and the object being measured are at 70°F. The mike is made of steel with a linear coefficient of expansion of $11 \times 10^{-6}/C°$. It is used to measure an aluminum piston with a diameter of 4 in. If the mike is 60°F and the piston is 90°F, how much error is there in the reading? If both are at 90°F? The piston has a coefficient of expansion of $24 \times 10^{-6}/C°$.

19. An inside mike has the same specifications as the one in problem 18, and is used to measure the diameter of a 4 in cylinder after boring and polishing. How far off is the reading if the mike is 60°F and cylinder wall is 105°F? Both mike and engine block have a linear coefficient of expansion of $11 \times 10^{-6}/C°$.

20. An exhaust pipe, muffler and tail pipe, together are 12 ft long. They are made of steel and have an operating average temperature of 230°F through-out the entire length above the air temperature. How much does the length increase during warm-up?

21. When water is heated from 40°F to 180°F, it is said to expand about ¼ pint per gallon. Is this consistant with table III in the Information Sheets? What is the volume coefficient of expansion of a 50% ethylene glycol antifreeze solution in $1/C°$, if it expands by 1/3 pint per gallon over the same temperature range?

22. A 21 gal steel gasoline tank on an automobile is filled from an underground tank at 50°F. On a hot summer day the temperature of the tank and gasoline increases to 120°F. How much gasoline will overflow?

NOTE: Unless otherwise instructed, use 14.7 lb/in^2 as atmospheric pressure in the following problems. Remember to use absolute pressure and temperature in gas expansion problems.

23. The volume of a tire is 1500 in^3 when the gauge pressure is 30 lb/in^2. What volume will this air occupy at atmospheric pressure at the same temperature?

24. Air pumped into a tank has a temperature of 45°C. The compressor pump stops when a gauge pressure of 150 lb/in^2 is reached. What will be the gauge pressure when the air has cooled to 20°C? Assume the change is isochoric.

25. A truck tire has a gauge pressure of 90 lb/in^2 at a temperature of 60°F. After running at high speed on a hot afternoon its temperature increases to 140°F. If the change is isochoric, what is the gauge pressure?

26. A gas is collected at 27°C and has a volume of 400 cm^3. At what temperature (Celsius) will its volume be 424 cm^3? The expansion is isobaric.

27. A cylinder of a diesel engine in an automobile contains 31.7 in^3 of air at bottom dead center. It has an absolute pressure of 14 lb/in^2 and a temperature of 200°F. What will be the temperature at top dead center when the air is compressed to 1.51 in^3 and an absolute pressure of 650 lb/in^2. The stroke is completed quickly enough, so the compression is approximately adiabatic.

28. A cylinder of a gasoline engine contains 48 in^3 of air-fuel mixture at 13 lb/in^2 absolute pressure and a temperature of 200°F as it starts the compression stroke. At 25° before the end of the stroke the temperature has increased to 490°F, while the volume decreased to 9 in^3. What is the pressure if the process is adiabatic? NOTE: Ignition occurs about 25° before the end of the stroke. If the ignition switch is shut off, the temperature and pressure will increase as the volume decreases to 5 in^3 at top dead center (9.6:1). If the engine isn't tuned correctly, the high temperature may cause the engine to continue to run (diesel effect).

ANSWER KEY (PROBLEMS)

Module T 1 TEMPERATURE AND THERMAL EXPANSION

1. 32°- 212°F, 0°- 100°C, 180 F° and 100 C°, 5/9

2. The rate at which heat flows from hand to object. The rate is normal at 70°F (room temperature). Below 70°F the rate of flow is faster than normal and the object feels cool or cold. Above 70°the rate of flow is less than normal and stops at 98.6°F, the object feels warm. Above 98.6°F the flow is from object to hand and the object feels warm to hot.

3. Glass bulb expands before heat gets to the mercury. Yes.

4. No.

5. A thermal expansion process during which time no heat is transferred into or out of the gas. Yes, approximately. Work is done on the rubber band. (Like bending a wire back and forth it gets hot).

6. 40°F

7. 50°F

8. 2 C°

9. 80.6°F - 68°F

10. 1089°F - 185°F

11. 12.2°F

12. 18.3°C

13. 104°F

14. 82°C

15. 538°C

16. 126°F

17. 0.015 in

18. 0.0013 in, 0.00059 in

19. 0.0011 in

20. 0.202 in

21. $40 \times 10^{-5}/C^{\circ}$ (compares with $37 \times 10^{-5}/C^{\circ}$), $54 \times 10^{-5}/C^{\circ}$

22. 0.83 gal or 3.3 quarts

23. 4561 in^3 or 2.64 ft^3

24. 137 lb/in^2

25. 106 lb/in^2

26. 45°C

27. 1000°F

28. 85 lb/in^2 (Note that this is 25° before TDC).

REPORT

Module T 1 TEMPERATURE AND THERMAL EXPANSION

The following brief report should be completed by students in Automotive and Diesel Technologies.

Nearly all modern high speed, high compression, short stroke, large bore engines use a piston made of an aluminum alloy. Thermal expansion of the piston presents a problem of maintaining the proper clearance between it and the cast iron cylinder wall. In some parts of the world, the internal parts of an engine may be at a temperature well below zero (Fahrenheit) on a cold winter morning. In normal operation the piston head is typically at a temperature of 450°F while the skirt must run cooler at about 230°F. Even in overheated condition, the piston must have proper clearance to prevent seizure or excessive friction. The coefficient of thermal expansion of aluminum is nearly double that of cast iron.

Look up in various technical books to find out how thermal expansion problems are taken care of in the design of pistons. Write a brief report (two or three paragraphs) describing how these problems are overcome. You should tell what happens if the piston expands too much or too little. Somewhere within your report describe the purpose of heat dams, horizontal and vertical slots. Tell what cam-ground pistons are. What is the purpose of the elliptical shape? What parts have barreled and tapered shapes? What is hoop stretching? Describe the purpose and action of struts, bands or belts in terms of differential expansion.

K.W. Stinson, Diesel Engineering Handbook, Business Journals, Inc., 12th ed., 1972
W.H. Crouse, Automotive Engine Design, McGraw-Hill Book Co., 1970
W.K. Tolboldt, L. Johnson, Automotive Encyclopedia, Goodheart-Wilcox, 1975
R.D. Brown, J.R. Daines, P.R. Rickert, Introduction to Automotive Technology, Holbrook Press, Inc., 1976

EXPERIMENTS

Module T 1 TEMPERATURE AND THERMAL EXPANSION

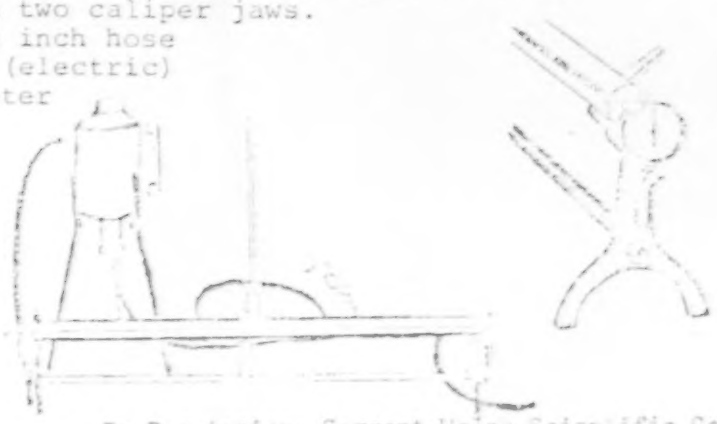
PURPOSE: The purpose of this experiment is to study, by experimenting with one specific material, the expansion that occurs in solids when their temperature is increased.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: Check to see if all the following equipment is available before you start.

1. Linear expansion apparatus (Sargent-Welch #1633A)
2. Meter stick with two caliper jaws.
3. Two lengths of ¼ inch hose
4. Steam generator (electric)
5. Celsius thermometer
6. Beaker



By Permission: Sargent-Welch Scientific Co.

INFORMATION: The change in length that occurs in a metal rod depends on the material, the change in temperature and the original length of the rod according to the following formula:

$$\Delta L = \alpha L \Delta T$$

In this experiment you will measure the original length (L), the change in length (ΔL) and the change in temperature (ΔT) and calculate the coefficient of linear thermal expansion. You will then determine the material the rod is made of by comparing your calculated value with several values in a table.

PROCEDURE:

1. Fill the boiler two-thirds full of water, connect one hose to the boiler only. Put boiler on its stand and plug into the wall socket. Put the free end of the hose into the beaker and secure with a piece of tape across top of the beaker. While water is heating, proceed with steps three through fifteen.

CAUTION: Be careful not to upset the boiler. Do not touch heating coils or the boiler, accidently.

NOTE: When the boiler is plugged in it usually makes a noise. If it doesn't begin heating right away, have the instructor check it for you.

2. Hold the meter stick with the small numbers to the left. Assemble the caliper jaws onto the meter stick and set one on the 20 mm line exactly; tighten the clamp screw.

3. The tube of the linear expansion apparatus is supported at each end in "V's". At the front is a dial indicator that reads in millimeters (mm). At the other end is a positioning screw with locknut. Loosen the locknut and back-off the screw three or four turns.

4. Retract the pointer of the indicator with one hand and lift the end of the tube clear of the front "V". Release indicator pointer gently and remove tube from rear "V".

5. Place tube flat on the bench away from the edge. Do not drop!

6. The tube has a cork in each end that supports a metal rod. Check to be sure the rod ends extend out of the cork slightly.

7. Measure the length of the rod with the meter stick to the nearest one-half millimeter. Place the fixed caliper jaw against one rod end. Slide the second caliper jaw against the other rod end and tighten it. Be sure the meter stick is parallel to the tube. Record the length on the data sheet.

8. Remove meter stick from tube and read setting of both caliper jaws. Record both readings. Replace tube into the "V's" of the stand, starting with the end that goes under the hold down spring. Hold the pointer of the indicator retracted as the tube is placed in the front "V". Then release the indicator tip.

9. Wet the bulb end of thermometer with a drop of glycerin. Slide a short piece of rubber hose over the thermometer for safety. Gently push the stopper onto the bulb end of the thermometer, with a twisting motion. The bulb only should extend into the tube near the rod. NOTE: The thermometer bulb should not rest on the rod.

CAUTION: Use care when handling the thermometer. It is very fragile.

10. Slide the tube back until the end of the rod rests against the positioning screw. Turn the screw to move the tube toward the indicator until the indicator hand turns about one half turn. tighten the locknut.

11. Insert hoses on each end of the tube. The loose end of one should be placed in the beaker; the other (with metal tube connector) should lay loose on the table. DO NOT CONNECT TO THE BOILER.

12. Gently move indicator tip about a sixteenth of an inch from the rod end and release it. Do this two or three times until the indicator reading is constant.

13. Turn the outer rim of the indicator to position the zero exactly under the indicator hand. Do not bump or even touch the apparatus from this point on.

14. Read and record the temperature on the data sheet.

15. Steam should be emerging from the hose on the boiler by now. If it is remove it from the beaker and connect it to the hose with the metal hose connector on it.

NOTE: Quickly, check the indicator reading. It should still read zero.

CAUTION: From this point on the boiler, steam jacket and hoses will be hot.

16. When the thermometer reading is constant (near 100°C) for two or three minutes. Read the indicator to the nearest 0.005 millimeter. Record this reading and the final temperature on the data sheet.

17. Unplug boiler and let apparatus cool while the data is analysed.

18. Calculate the coefficient of linear thermal expansion for the rod.

19. Using the table below, identify the material the rod is made of from its coefficient of linear expansion.

COEFFICIENT OF LINEAR EXPANSION

Material	α (1/C°)
Aluminum	24×10^{-6}
Bronze	18×10^{-6}
Copper	17×10^{-6}
Iron (wrought)	12×10^{-6}
Steel	11×10^{-6}

20. Dismantle equipment, empty water and return equipment to the drawer.

CAUTION: Be careful of hot boiler and hot water!!

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: T 2

Title: HEAT AND CHANGE OF STATE

Module Contents:
1. Heat units
2. Heating value of fuels
3. Specific heat
4. Latent heat
5. Change of state

Program: This module was prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to study heat as a form of energy. Heat is produced by burning fuel, by doing work against friction and against elastic flexing and by electric currents. The efficiency is reduced when energy is lost in the form of heat. This module is prerequisite for the next module on heat transfer.

Producer: Gene Waring

Date Produced: March 1977 -

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module T 2 HEAT AND CHANGE OF STATE

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define the British thermal unit and the calorie as units of heat energy.
2. Define the mechanical equivalent of heat and state its accepted values in both British and metric units.
3. Define the heating value of
3 fuels.
4. Define specific heat for solids and liquids. Describe the difference between specific heat at constant volume and at constant pressure for gases.
5. Define heat of fusion and heat of vaporization.
6. State the law of mixtures in terms of the law of conservation of energy and solve problems involving continuous flow calorimeters.
7. Define freezing, melting, boiling and condensation.
8. Describe the processes in objective 7 in terms of the cooling or heating effect they produce.
9. Define freezing point and boiling point and describe the effect of pressure on each. Define cavitation.
10. Solve various problems associated with the formulas and definitions in objectives 2,3,4,5 and 6.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of heat. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet: Read the information section of the lab instructions. All the textbooks listed below cover most of the objectives of this module. A table of various heat constants is printed on green paper for your convenience. Read your text before reading the information sheets.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 14, pages 352-376 and chapter 16, section 16.1, pages 397-401.

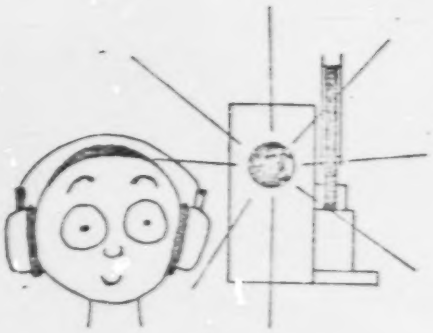
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 15, sections 15.8-15.12, pages 200-206 and chapter 16, pages 210-219.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, sections 16.3-16.6, pages 213-219 and chapter 18, pages 236-242.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 14, sections 14.2-14.5, pages 215-228. Also see Information section of the lab instructions.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read chapter 17, sections 17.2-17.5, pages 263-271.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Conditions Necessary For Combustion (Doubleday Multimedia 13155)
B. Heat is Produced in Different Ways (Doubleday Multimedia 13135)
C. Heat Can Do Work (Doubleday Multimedia 13145)
D. Most Solids Melt (Doubleday Multimedia 13015)
E. Boiling Points of Water (Doubleday Multimedia 13095)
F. Gases Condense as They Cool (Doubleday Multimedia 13065)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving heat problems. The problems from number five on are applied to your technology.

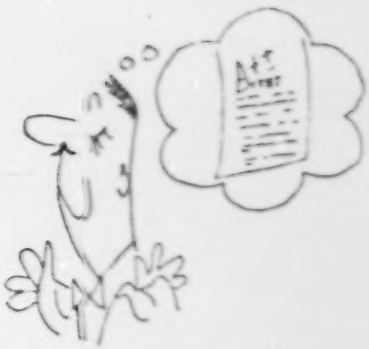
IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about the mechanical equivalent of heat. Electrical, electronic and electromechanical students must complete Experiment II, also. Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (T 2) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)



Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module T 2 HEAT AND CHANGE OF STATE

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The British thermal unit is the amount of heat required to raise the temperature of 1 gal of water one degree.

T - F 2. Melting is a cooling process because heat is drawn from the surroundings thereby cooling the surroundings.

T - F 3. When a liquid is boiling, turning up the flame will force the liquid to boil at a higher temperature.

T - F 4. When a substance begins to change state, its temperature will neither rise nor fall until the change is completed.

T - F 5. The mechanical equivalent of heat is kinetic energy.

6. When a vapor condenses into a liquid

a) its temperature rises c) it emits heat

b) its temperature drops d) it absorbs heat

7. The specific heat of aluminum is 0.22 Btu/lb F°. How much heat in British thermal units is required to raise the temperature of a 100 lb casting from 70°F to 1220°F?

a) 253 c) 1150

b) 25 300 d) 115 000

8. The latent heat of fusion of copper is 43 kcal/kg. Express this in British thermal units per pound.

a) 77.4 c) 170

b) 94.8 d) 1.80

9. How much heat is required to raise the temperature of 6 gal of water (50 lb) from 70°F to 212°F and then boil away 10% (5 lb)? The specific heat of water is 1 Btu/lb F°and the latent heat of vaporization is 970 Btu/lb.

10. Water has a specific heat of 1 Btu/lb F°. How many cubic feet of natural gas is necessary to raise the temperature of 250 lb of water (30 gal water heater) from 40°F to 160°F? The fuel value of natural gas is 1100 Btu/ft^3. Assume the water absorbs all the heat from the flame.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 2 HEAT AND CHANGE OF STATE

Question - Answer	If you missed this question, you are directed to these learning activities
1. F	I Reading
2. T	I Reading
3. F	I Reading or II Listening/Viewing
4. T	I Reading
5. F	I Reading and V Lab Experiment
6. c	I Reading or II Listening/Viewing
7. b	III Solving Problems
8. a	III Solving Problems
9. 11 950 Btu	III Solving Problems
10. 27.3 ft^3	III Solving Problems

INFORMATION SHEET

Module T 2 HEAT AND CHANGE OF STATE

Table 1 Heating values of various fuels

Fuel	Btu/lb	Btu/gal	Btu/ft³	kcal/kg	kcal/l
Coal*	13 000			7200	
Wood*	6000-8000			3300-4400	
Diesel fuel	192 000	145 000		10 700	9600
Kerosene	19 800	135 000		11 000	9000
Gasoline	20 500	115 000		11 400	7650
Acetylene	19 800		1450**	11 000	12.9**
Hydrogen	57 900		325**	32 200	2.9**
Natural gas*	14 100		1200**	7800	10.7**
Propane	19 100		2400**	10 600	21.4**

* varies - values given are typical or average

** volume at 0°C and 1 atm pressure

Table 2 Heat properties of various materials

Material	Specific heat	Heat of fusion (kcal/kg)	Heat of vaporization (kcal/kg)	Melting point (°C)	Boiling point (°C)
Air	0.240 (Cp) 0.171 (Cv)		51	-350	-315
Alcohol (ethyl)	0.58	25	205	-115	80
Aluminum	0.22	77		660	2060
Brass	0.092				
Copper	0.093	43		1080	2300
Gasoline			75		80
Ice	0.50			0	
Iron & Steel	0.11	30		1500	2980
Lead	0.030	6	175	330	1620
Mercury	0.033	3	70	-40	360
Steam	0.48		540		100
Stone	0.19 (av)				
Water	1.00	80	540	0	100

Table 3 Boiling point of water at various applied pressures

Absolute pressure (lb/in^2)	Boiling point (°C) (water)	Boiling point (°C) (50% ethylene glycol)
0.089	0	
0.18	10	
0.34	20	
1.0	38.9	
1.8	50	
2.9	60	
4.5	70	
6.7	80	87
10.2	90	97
14.7	100 (normal)	107
20.8	110	117
25	116	123
39.3	130	137
50	138	145
69.2	150	
75	153	
89.2	150	
100	164	
200	194	
300	214	
400	229	
500	242	

Table 4 Freezing point of water at various applied pressures

Absolute pressure (atmosphere)	Freezing point (°C)
0	0
400	-3
600	-5
1100	-10
1750	-15
2150	-20

Table 5 Calorie values of various foods

Food	Energy (Cal)*	Food	Energy (Cal)*
milk (1 cup)	90	hamburger (3 oz)	245
carbonated beverage (8 oz)	70	steak (3 oz)	400
beer (8 oz)	115	frankfurter (1)	160
bread (1 slice)	60	bacon (2 slices)	100
butter (1.5 tsp)	50	ham (3 oz baked)	250
American cheese (1 slice)	110	fish stick (1)	150
egg (fried)	110	string beans (1/2 cup)	20
apple pie 1/6	400	baked beans (1/2 cup)	120
apple	90	corn (1 ear)	80
banana	130	celery (1 stalk)	10
peach	40	tomato (small)	60
peanuts (1/2 oz)	90		

* Food calories are equal to kilocalories and usually written with a capital C.

Table 6 Caloric expenditures for various activities

Activity	Calories per hour*
Sitting at rest	15
Standing relaxed	20
Dressing-undressing	33
Walking	130-200
Cycling	180-300
Swimming	200-700
Running	500-930

* Rates listed are for average 128 lb woman or 154 lb man.

CAVITATION: Whenever a liquid evaporates, the vapors create pressure above the liquid. This pressure is called the vapor pressure of the liquid and it depends on the temperature. If the temperature is such that the vapor pressure is equal to the applied pressure then the liquid boils. See table 3. This table gives the applied pressure on water and the corresponding boiling point. The table also gives the vapor pressure of water at given temperatures.

Example: What is the boiling point of water used as a coolant in an automobile if the pressure cap provides relief at 25 lb/in^2 absolute.

Solution: Table 3 gives a boiling point of 116°C (240°F). Note: Antifreeze solutions would have a different boiling point for the same pressure.

Example: What is the vapor pressure of water at 50°C (122°F)?

Solution: Table 3 gives a vapor pressure of 1.8 lb/in^2.

If the temperature of water is 50°C, the water would boil if the applied pressure drops to 1.8 lb/in^2. Water will suddenly flash into a vapor even below the surface forming vapor bubbles. The bubbles form continuously and rise to the surface. This process is known as boiling.

In a moving liquid, pressure may drop suddenly. The drop in pressure may be due to the venturi effect or the internal swirls and eddies produced in turbulant flow. The pressure is much lower at the center of such swirls. This usually occurs on the inlet side of a pump or turbine near the blades or propellers. It also occurs in needle valves and jet nozzles.

The sudden vaporization of liquid in such situations is called cavitation and it occurs when the pressure drops below the vapor pressure of the liquid which depends primarily on the temperature. Such cavities do little harm except when they collapse near metal surfaces. They usually collapse downstream from when they were formed in regions of higher pressure.

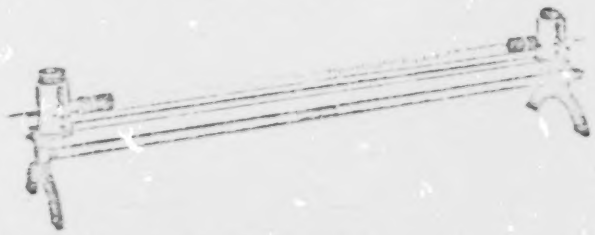
During collapse there is a sudden momentary very high pressure on the metal impeller blades, jets, turbine blades, etc. The effect may cause mild to severe pitting of the metal on the back of the turbine blade or jet opening. Extreme cavitation occurs when it spreads over large areas and causes instability, vibration, noise and very rapid wear of the metal parts.

HEATING A GAS

The formula $Q = mc\Delta T$ gives the heat (Q) required to change the temperature (ΔT) of a certain mass (m) where c is the specific heat used for solids, liquids and gases. Cases, however, can be thermally changed by several processes. (See module T 1). The formula is not applicable to isothermal, adiabatic and throttling processes. There is no temperature change in isothermal processes and no heat is added in the other two.

In an isochoric process (constant volume) the heat added goes entirely to raising the temperature of the gas. In an isobaric process (constant pressure), some of the heat increases the temperature while some of it does work on the gas as it changes volume. More heat is required to raise a certain mass of gas through a given temperature range when the process is isobaric than if the process were isochoric. The specific heat at constant volume (C_v) of air is 0.171 Btu/lb F°, for example, while the specific heat at constant pressure (C_p) is 0.240 Btu/lb F°. Air inside a TV set or radio is heated isobaricly while air in a sealed container is heated isochoricly, for example.

CONTINUOUS FLOW CALORIMETERS



Continuous flow calorimeter
By permission: The Sargent-Welch Scientific Co.

The device shown in the diagram is a continuous flow calorimeter. The source of heat is a resistance wire enclosed in a glass tube and connected to insulated binding posts. Water or other liquid coolant flows through the tube, continuously, through the inlet and outlet tubes. An outer glass tube provides a dead air space to eliminate heat loss. Thermometers measure the temperature of the flowing water at the inlet and outlet tubes.

The inlet is connected to a constant level tank to provide constant rate of flow of coolant. Once temperature equilibrium is established, the rate of flow (R) can be determined by collecting a volume (V) of coolant over a measured period of time (t). The total heat energy absorbed by the coolant is given by the formula.

$$Q = dVc\Delta T \qquad 1$$

Where d is the density and the product (dV) is the mass of coolant collected. The rate of heat absorbtion (P)(power) by the coolant is Q/t:

$$Q = dRc\Delta T \qquad 2$$

Where P will have units of Btu/s, cal/s, etc. These units can easily be converted to ft lb/s, watts, horsepower etc. The power provided by the flow of electric current is equal to the rate at which heat is absorbed by the coolant.

Example: In the calorimeter described above, 2 ℓ of water is collected in 1.75 min. The inlet temperature is 10°C and the outlet temperature is 15°C. The density of water is 1 kg/ℓ and the specific heat is 1 kcal/kg C°. Find the rate of heat absorbtion in kcal/s and the electric power in watts.

Given: $V = 2\ \ell$
$t = 1.75\ \text{min} = 105\ \text{s}$
$T_1 = 10°C$
$T_2 = 15°C$
$d = 1\ \text{kg}/\ell$
$c = 1\ \text{kcal/kg C}°$

Solution: $R = V/t = 2\ell\ /105\ \text{s} = 0.019\ \ell/\text{s}$
$P = dRc\Delta t$
$= (1\ \text{kg}/\ell)(0.019\ \ell/\text{s})(1\text{kcal/kg C}°)(5\ \text{C}°)$
$= 0.0952\ \text{kcal/s}$ (Rate of heat absorbed)
$P = (0.0952\ \text{kcal/s})(4186\ \text{J/kcal})$
$= 399\ \text{W}$ (electric power supplied)

Energy gain or power gain can be determined in any device in which fluids absorb heat if the rate of flow and inlet and outlet temperatures are known. An example is the energy absorbed by water flowing through a water turbine dynamometer. Energy loss or power loss can be determined in the same way in devices that have a cooler outlet temperature than inlet temperature. The radiator on a car is an example.

PROBLEMS

Module T 2 HEAT AND CHANGE OF STATE

1. The units of specific heat are: Btu/lb F°, cal/g C°and kcal/kg C°. Why are the numerical values of the specific heat for a given substance identical?

2. Why does steam at 100°C produce a much worse burn than water at 100°C?

3. Under what circumstances can heat be added to a substance without changing the temperature?

4. What does the word regelation mean? How is it involved in the packing of a snowball?

5. What does the word cavitation mean? Exactly how does cavitation cause metals to wear?

6. A pot of water is boiling on the stove. If you turned the flame up will the water boil at a higher temperature? Explain.

7. When a vacuum is produced over a beaker of water in a bell jar, the water boils. After several minutes the water stops boiling. Why? What has happened to the temperature of the water? Where does the heat of vaporization required by the boiling process come from in this case?

8. Salt is sprinkled on some 32°F ice in a beaker. In a few minutes some of the ice has melted. The temperature of the ice-water brine in the bottom is about 18°F. The temperature of the ice above the brine is about -4°F. Where does the heat of fusion required to melt the ice come from?

9. If there were about 11.5 lb of ice in the beaker in problem 8 and 1.5 lb melts, what must be the resulting temperature of the ice that remains unmelted? Assume all the heat required to melt the 1.5 lb came from the remaining 10 lb of ice.

10. If the specific heat of the human body is 0.9 kcal/kg C°, how many kilograms of water would have to evaporate from a 55 kg woman to lower her temperature by 1 C°? From a 75 kg man? The latent heat of vaporization at body temperature is 580 kcal/kg.

11. If the man and woman in problem 10 each consumed 1600 kcal of food in one day, how much would their temperature rise if all the food energy were converted to heat? Assume no heat is lost by any method.

12. About how many hours could a person walk using only the food energy supplied by one fried egg, one slice of buttered bread and one cup of milk? Assume none of the energy is converted to heat. See tables 5 and 6 in the Information Sheets.

13. Plot a graph of the information in table 3 of the Information Sheets up to 50 lb/in^2 Plot the boiling point of water and of a 50% ethyline glycol solution on the same graph (vs applied pressure). From the graph, determine the boiling point of water and of a 50% ethylene glycol solution if a 16 lb/in^2 (gauge) pressure cap is used on the radiator of a car at sea level. What is the boiling point of each if the same pressure cap is used on a car in eastern Nebraska where the atmospheric pressure averages 14.0 lb/in^2?

14. Is cavitation a problem on the input side of a water pump on a gasoline or diesel engine? Does cavitation occur in any other part of the cooling system? How important is the use of a proper pressure cap on the radiator in reducing cavitation? Will the addition of chemical additives inhibit cavitation?

15. Refer to table 1 in the Information Sheets Gasoline has a higher heating value than diesel fuel when measured in Btu/lb. The situation is reversed, however, when the heating value is measured in Btu/gal. Explain why.

16. About 35% of the heat produced by combustion in a diesel engine is lost to the coolant, to the air blowing over the engine and to radiation from the engine. The corresponding figure for a gasoline engine is 35% also. On a diesel engine the loss to the exhaust is about 28% and for a gasoline engine, 35%. The remainder is converted to useful work on the piston for each type engine. Convert these percentages to Btu per gallon of diesel fuel for the diesel engine and to Btu per gallon of gasoline for the gasoline engine.

17. Some of the heat loss in a gasoline engine is to the gasoline while it is still in the intake manifold. The gasoline must be vaporized before entering the cylinder. How much heat is required to vaporize 1 gal of gasoline if its density is 5.75 lb/gal? NOTE: The cooling effect accompanying the vaporization of gasoline allows a more dense air-fuel mixture into the cylinder on each intake stroke, resulting in a more powerful explosion.

18. A light truck is traveling 50 mi/h on a day when the outside (ambient) temperature is 45°F. The temperature of the coolant at the radiator inlet is 160 F (170° thermostat) and at the radiator outlet it is 120°F. If the pump moves the coolant at a rate of 11.25 gal/min and it has a density of 8.8 lb/gal, find the amount of heat removed by the air stream through the radiator each minute. The specific heat of the coolant is 0.8 Btu/lb F°.

19. The truck in the previous problem is carrying a 2.5 ton load and gets only 10 mi/gal of gasoline. At 50 mi/h, how much time does it take to burn 1 gal of gasoline? How much heat is carried away by air blowing through the radiator for each gallon of gasoline burned? The heat removed per minute is 3170 Btu.

20. The heat removed by the radiator on the truck in the previous problem is 38 000 Btu for each gallon of gasoline burned. An additional 2250 Btu is transferred to the air blowing over the engine and by radiation. What percent of the energy available in a gallon of gasoline is lost by cooling? See table 1 in the Information Sheet for heating values of fuels.

21. What is a vapor-lock in a fuel pump on a gasoline engine? Are vapor-locks related to cavitation? Explain?

22. How many kilocalories per minute must be removed from an air conditioner radiator on a car if it cools 4.9 m^3 of air per minute from 37°C to 7°C and also condenses and removes 1 kg/hr of water vapor from the air. The density of air is 1.2 kg/m^3.

23. An automobile with a mass of 1800 kg is traveling 90 km/h. How much kinetic energy does it have? ($E_K = \frac{1}{2}mv^2$) In sudden braking about 75% of a car's energy is converted to heat and absorbed by the four brake drums. If each drum has a mass of 8 kg not including the hub, what will be the average temperature of the drums when the automobile comes to a sudden stop if they were at 40°C before braking began? The specific heat of the iron drums is 0.11 kcal/kg C°.

24. A diesel engine is mounted to a dynamometer. The brakes system on the dynamometer is a water turbine. Water flows through the turbine at 4.07 gal/min for cooling purposes. The churning in the turbine heats the water from 50°F to 150°F. If the water flowing through the turbine absorbs all the output energy of the engine, what brake horsepower is the engine developing?

ANSWER KEY (PROBLEMS)

Module T 2 HEAT AND CHANGE OF STATE

1. See definition of heat units and specific heat.

2. Heat is transferred at the boiling point (latent heat of vaporization) by steam. A drop in temperature accompanies heat transfer from water.

3. Any isothermal process or during change of state.

4. Drop in freezing point due to high pressure.

5. See Information Sheet.

6. No, it just boils faster.

7. Temperature has dropped to the boiling point. Decreases. It must come from the kinetic energy of the molecules since no heat is being added so the temperature drops.

8. See problem 7.

9. -11.2°F (Since some heat came from the melted ice, the temperature is not quite this low).

10. 91.7 g, 125 g

11. 32.3 C°, 23.7 C°

12. 1.6 - 2.4 hrs

13. 121.6° - 126.6°F and 120.9° - 127.9°F

14. Usually not if the proper pressure cap is used. In water jacket surrounding hot cylinder walls. Very important. Yes. See K.W. Stinson, Diesel Engineering Handbook, Business Journals, Inc., 12th ed., 1972 or H.E. Ellinger, Automotive Systems-Fuel, Lubrication and Cooling, Prentice-Hall, Inc., 1976.

15. Density of diesel fuel is 7.2 lb/gal. For gasoline, it is 5.75 lb/gal.

16. Cooling - 40 250 Btu/gal, 50 750 Btu/gal Exhaust - 40 250 Btu/gal, 40 600 Btu/gal Useful work - 34 500 Btu/gal, 53 650 Btu/gal

17. 775 Btu, 0.67%

18. 3170 Btu/min

19. 12 min, 38 000 Btu

20. 35%

21. When enough heat is transferred from the engine to the fuel pump (inlet side), the gasoline boils because of the temperature and low pressure. The pump will not pump the vapor. See Information Sheets.

22. 51.3 kcal/min

23. 68.8°C

24. 79.9 hp

EXPERIMENTS

Module T 2 HEAT AND CHANGE OF STATE

PURPOSE: The purpose of this experiment is to study the mechanical equivalents of heat. Work is done against friction causing heat to form in a copper drum. Both the work done and the heat produced is measured and compared.

CAUTIONS:
1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horse play is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EXPERIMENT I: MECHANICAL EQUIVALENT OF HEAT

EQUIPMENT: Check to see if all the following equipment is available before you start. If you have any question, ask the instructor.

1. Base with handle (Ealing 21-2456)
2. Copper block calorimeter
3. Weight and hangar (about 10 kg)
4. Cord with attached slide, S hook and rubber band
5. Thermometer and guard
6. Red plastic cap
7. Vernier caliper

INFORMATION: In 1843, James Prescott Joule performed a famous experiment which showed that work and heat were equivalent. He used a calorimeter with an internal paddle wheel which could be turned by the pull of a falling weight. The work done by the falling weight which churned the water in the calorimeter. The temperature of the water was raised as a result of the churning. He calculated the amount of heat produced from the known amount of mechanical work.

The ratio of the mechanical work done (W_K) to the amount of heat produced (Q) is called the mechanical equivalent of heat (J) (or Joule's constant).

$$J = \frac{W_K}{Q}$$

The value of J is 778 ft lb/Btu or 4186 J/kcal in the British and MKS measuring systems, respectively.

Heat is always produced when work is done against friction or when work is done while bending, twisting, compression or stretching a material. Tires get warm from flexing; wire gets hot when bent back and forth; rails get warm when a train passes over them; a nail gets warm when pounded with a hammer; bushings get warm from the friction; automatic transmission oil gets very hot from the constant turbulance.

Whenever energy is transmitted from one part of a machine to another, some of it is converted to heat. The heat causes a rise in temperature of the material. The heat energy is then transferred away from the machine and lost. The work output of a machine can never be as great as the input.

In this experiment, all the work is done against friction. The amount of work done and the heat produced are measured and compared. A preliminary experiment is performed to note the temperature rise. The apparatus is then cooled below room temperature so it will absorb heat from the room half of the time. As the temperature of the apparatus rises above room temperature it then gives off heat to the room. The two effects cancel giving good results for the mechanical equivalent of heat.

PROCEDURE:

CAUTION: Do not install the thermometer until step 8. Use extreme care with it because no other thermometer will fit the apparatus.

1. Clamp the base (with handle) to the edge of a sturdy table or bench as shown in the accompanying diagram so the load can hang freely.

2. Unscrew the copper drum and measure its diameter and mass. Record these values on the data sheet. DO NOT HANDLE THE DRUM ANY MORE THAN NECESSARY. IT ABSORBS HEAT FROM YOUR HAND.

3. Wind the nylon cord to the copper drum. Start from the handle end and wind five or six turns without overlapping. Wind clockwise as viewed from the handle.
   NOTE: The loop end of the cord with the slider attached should hang down near the weight. The end of the cord with the attached rubber band should run over the top

4. Attach the S hook to the weight hanger and the rubber band to the anchor-pin on the back of the base. You may need to turn the handle to make both connections.

Mechanical equivalent of heat apparatus
By permission: The Ealing Corporation.

5. Rotate the handle to lift the weight. The weight should lift completely off the floor and there should be little or no tension in the rubber band. Make adjustments as necessary. Don't rotate the handle more than necessary.

6. Check to see if the cord "travels" to one end of the drum. If it does, the apparatus is not level. Make adjustments by placing cardboard shims under the low side.

7. Insert the U-shaped thermometer guard in the two holes in the base under the copper drum.

8. Slide the red plastic sleeve on the thermometer. Place a drop of glycerin on the thermometer bulb for good thermal contact and attach the thermometer to the copper drum with the sleeve. Push the thermometer in until it touches the bottom of the hole. HANDLE THE THERMOMETER WITH CARE.

9. Record the temperature. It should be near room temperature.

10. Rotate the handle 100 turns. Do this quickly enough to finish in about one minute.

11. When the temperature of the drum stops rising, record the temperature and the rise in temperature.

12. Disassemble the apparatus and cool the drum to a temperature equal to one-half the temperature rise below room temperature. Record the temperature.

NOTE: Cooling can be accomplished by running cold water over the drum. The temperature may go below that required but by the time you dry the drum and reassemble the apparatus it should be near the correct temperature. Warm it with your hands if necessary. THE DRUM MUST BE DRY BEFORE RE-ASSEMBLING.

13. Turn the handle exactly 100 turns. Try to complete the 100 turns in about one minute.

14. As soon as the 100 turns are completed, lower the weights to the floor without further slipping of the cords against the drum.

15. Carefully observe the temperature and record the highest temperature reached by the drum.

16. Record the weight. Include the weight of the hangar and the holding clip. Most of the weights are marked. The total weight is the frictional force acting on the copper drum.

17. Calculate the work done against friction. The distance traveled is: 100 turns times the circumference.

18. Calculate the heat produced ($mc\Delta T$). The specific heat of copper is 0.093 kcal/kg C°.

19. Calculate the mechanical equivalent of heat.

20. Compare your calculated value with the accepted value by finding the percentage error. Discuss the principal sources of error.

Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: T 3

Title: TRANSFER OF HEAT

Module Contents:
1. Conditions for heat transfer
2. Conduction
3. Convection
4. Radiation
5. Law of cooling

Program: This module has been prepared especially for students in:

1. Automotive Technology
2. Diesel Technology

Purpose: The purpose of this module is to study the transfer of heat energy. Heat is produced by combustion, friction and the flow of electric currents in automotive and diesel equipment. Huge quantities of heat must be removed or transferred for efficient operation. Repair, overhaul or alterations must be performed carefully to insure the proper flow of heat. The transfer of heat is very important in automotive and diesel industries.

Producer: Gene Waring

Date Produced: March 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module T 3 TRANSFER OF HEAT

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Distinguish between temperature, heat and internal energy.
2. State the law that determines the direction of heat flow between two objects.
3. Describe each of the heat transfer processes: conduction, convection and radiation.
4. Understand that heat current is the rate of flow of heat and is expressed in units of power.
5. State the basic formulas for heat current (I) for each heat transfer process.
6. Solve various applied conduction, convection and radiation problems using the formulas in objective 5.
7. Describe the difference between good heat conductors and insulators and good radiators and poor radiators.
8. State Newton's law of cooling and solve various problems dealing with cooling.
9. Describe the nature of a heat sink and define such terms as: heat path, thermal connection, heat dam and temperature hill.
10. Describe the use of fins, fans, louvers, black paint, silver paint and a vacuum in heat transfer.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of heat transfer. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read all of chapter 15, pages 380-394 and chapter 16, section 16.3 pages 404-405.

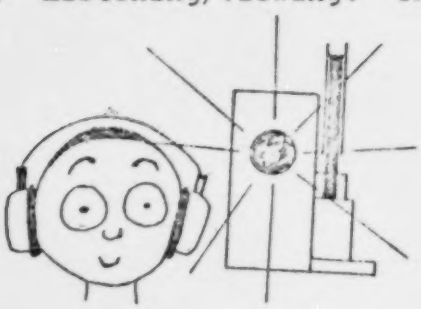
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read all of chapter 17, pages 222-231 and chapter 18, section 18.8, pages 241-242.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, section 16.4 pages 214-215 and Information Sheets (A).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 15, sections 15.7, pages 251-257 and chapter 16, section 16.3, pages 270-271.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 20, sections 20.1-20.3 and chapter 19, section 19.2, pages 297-298.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Convection In Liquids (BFA-Ealing 82-0050)

B. Temperature Waves (BFA-Ealing 80-2165)

C. Infra-Red Radiation (EBE S-81437)

D. Heat is Reflected and Absorbed (Doubleday 13115)

E. Heat Travels by Conduction, Convection and Radiation (Doubleday 13105)

F. Materials Conduct Heat at Different Rates (Doubleday 13125)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving heat transfer problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is no experiment in this module.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module T 3 TRANSFER OF HEAT

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. In order for heat to flow from one object to another, the two objects must contain different amounts of heat.

T - F 2. Conduction is the process in which heat energy is transferred from particle to particle without the actual transfer of material.

T - F 3. Natural convection involves the movement of a part of a liquid or gas which has a temperature that is different from the rest of the fluid.

T - F 4. Metals are better emitters of radiation than any other substance.

T - F 5. Newton's law of cooling applies to an object if the transfer of heat from it is by radiation only.

6. The materials with the highest coefficient of conduction are the:

a) metals
b) non-metal solids
c) porous solids
d) liquids

7. Which method of heat transfer is most involved when fans or pumps are used in industrial equipment such as a water pump on an automobile engine.

a) Conduction
b) Natural convection
c) Forced convection
d) Radiation

8. Find the total amount of heat energy in Btu that escapes through a window in one day if the heat current is 25 Btu/min.

a) 600
b) 1500
c) 2 160 000
d) 36 000

9. A solid concrete wall is 15 cm thick and has an area of 25 m^2. If the temperature difference averages 30 C°, find the heat current through the wall. ($K = 0.0004$ kcal/s m C°.)

10. An electric motor operates at a temperature of 55°C when used outdoors with an air temperature of -10°C. After being shut off, it cools to 50°C in 4 min. How much time is required for it to cool from 50°C to 45°C?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 3 TRANSFER OF HEAT

Question-Answer		If you missed this question, you are directed to these learning activities
1.	F	I Reading
2.	T	I Reading or II Listening/Viewing
3.	T	I Reading or II Listening/Viewing
4.	F	I Reading or II Listening/Viewing
5.	F	I Reading
6.	a	I Reading or II Listening/Viewing
7.	c	I Reading or II Listening/Viewing
8.	d	III Solving problems
9.	2 kcal/s 120 kcal/min	III Solving problems
10.	5.26 min	III Solving problems

INFORMATION SHEET

Module T 3 TRANSFER OF HEAT

Heat is produced whenever work is done against the force of sliding friction (in bushings or brakes, for example) or rolling friction (ball bearings), in the churning of turbulant fluid flow (automatic transmissions), in the elastic flexing or cutting of materials (tires, drill bits, etc.) and when electric current flows through a conductor (power resistors, diodes, transformers, etc. In most cases where energy is converted to heat by any of these methods, the heat is unwanted. The heat must be removed as it is produced or the objects' temperature will increase to a point where it operates inefficiently, is damaged or is destroyed.

Part of the heat that is produced on purpose by combustion of fuels (gasoline or diesel engines) or in nuclear reactions (power plants) is not utilized 100% and must be carried away. Even heat that is not produced by machinery and other equipment may be undesirable in certain places (food, living spaces) and must be removed by refrigeration.

In other cases, heat that is produced (on purpose or not) must be prevented from traveling along particular paths to critical areas or confined to a certain space. Heat diversions or heat dams may be used. A pair of pliers is used to hold a conductor while soldering connections. Most of the heat travels into the needle nose of the pliers instead of along the conductor where it could damage insulation and other electronic components. When copper pipe is being soldered with a torch, a wet rag will prevent excessive heat from reaching the wooden floor in a home.

When a torch is used to repair panels on an auto body an aqueous asbestos compound is used to create a heat dam to isolate the area being heated. This prevents buckling of the metal and protects rubber, glass, upholstery, paint, etc. The skirt of a piston must run cooler than the piston head to prevent excessive thermal expansion. A groove is cut around the piston above the top ring to reduce the cross section of the heat path. In addition a horizontal slot is cut below the bottom ring on both the front and back "sides". The piston head may operate at a temperature of 450°F while the entire skirt is less than 250°F. Insulation in a house is effective as a heat dam when recommended thicknesses are used.

The transfer of heat is an important subject. The following discussion gives more details about the processes involved and the conditions under which the transfer of heat will take place.

HEAT AND INTERNAL ENERGY

The internal energy of a material is the total energy within it in the form of kinetic energy of the molecules and the potential energy of attraction between the molecules. Whenever two kinds of material are at the same temperature, the kinetic energy of the molecules is the same. The kinetic energy may be in the form of translational, rotational or vibratory motion. Light molecules move faster than heavier ones when their kinetic energy is the same.

Heat is energy which is in the process of being transferred from one object to another or from one part of an object to another as a result of temperature difference. It is incorrect to say that an object contains, possesses or has a lot of heat in it. It has internal energy within it. You may feel the heat being transferred from hot water to your hands when you plunge your hands into it. The internal energy of the hot water will be reduced and its temperature drops slightly as a result. You are not feeling the internal energy of the water. Instead you feel the heat being transferred to your hands.

If heat flows into or out of an object, its temperature changes unless freezing, melting, vaporizing or condensing is involved. Heat flow does not affect the temperature during a change of state. Once the transfer of heat is finished, the object will have undergone a change in its internal energy, either kinetic (temperature change) or attraction (change of state).

THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics usually deals with the fact that although work can be completely converted to heat, heat cannot be completely converted into work. The kinetic energy of a car is completely converted to heat by the brakes and other frictional forces. The work done by a drill bit is all converted to heat. The energy used by a TV set is all converted to heat. The 2% or so converted to sound and light is absorbed by the air, walls and furniture in the room and changed to heat within seconds. However when heat is converted to work, only part is converted. Of all the heat produced by combustion in a gasoline engine, only about 30% actually does work on the pistons. The rest is dumped into the atmosphere by the exhaust or cooling system. A diesel engine will convert to work about 35% of the heat produced.

The greatest efficiency of any engine depends on the temperature difference between the hot cylinder and the cooler exhaust. Since the melting point and strength of metals determine the upper limit of high temperature and the atmosphere determines the lower limit for the cold, the efficiency never approaches 100%.

The internal energy of the atmosphere or the ocean is an enormous amount. It cannot be converted to work by any kind of engine, however, unless there is a colder reservoir into which some of the energy could be transferred. No process is possible in which the only result is the transfer of heat from a cold object to a warmer one. This statement is equivalent to the usual wording of the second law of thermodynamics. It is the relative temperature of two objects that determine the direction of heat flow in any natural process: always from hot to cold. The greater the temperature difference the greater the rate of flow.

The total amount of internal energy possessed by the two objects makes no difference. A lake of water frozen over in the winter time, for example, contains vastly more internal energy than a pot of boiling water. If the pot were submerged through a hole in the ice,

heat would immediately be transferred from the pot to the lake until they came to thermal equilibrium.

Heat always flows from an object at a higher temperature to one at a lower temperature or from a region of higher temperature in a given body to a region that is cooler. The transfer of heat can occur by three different processes: conduction, convection and radiation.

HEAT TRANSFER

1. Conduction is the process in which energy is transferred from particle to particle without the actual transfer of material. Metals conduct heat with the help of freely moving electrons.

2. Natural convection is the movement of the material that contains the energy caused by the action of gravity (buoyancy) on the thermally expanded material (fluids).

3. Forced convection is the movement of the material containing the energy when the movement is forced by pumps, fans, etc.

4. Radiation is the movement of energy through space without the use of a carrier material. The energy consists of electromagnetic waves transmitted from an emitter to an absorber.

CONDUCTION:

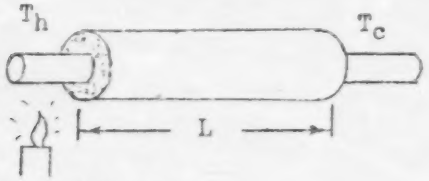


Fig 1 Conduction

If the end of a rod is heated as in figure 1, the hot molecules on that end will vibrate at a very rapid rate. They bump neighboring molecules and transfer energy in the process causing them to vibrate more rapidly, also. These molecules transfer energy to their neighbors by the same process and so on until the other end of the rod becomes warn. This is the process of conduction. Only the heat energy is transferred since the molecules can only vibrate in a fixed position.

Suppose the rod is insulated (see figure 1) and the heat flows in such a way as to maintain a fixed temperature difference $E = t_h - t_c$, where t_h and t_c are the hot and cold temperatures. The thermal resistance (R) is given by the formula $R = L/KA$ where K is the coefficient of conductivity of the material, A is the cross-sectional area and L is the distance the heat travels. The rate of flow or heat current (power) is given by $P = Q/t$ where Q is the amount of heat that flows in time t. The units of heat current are Btu/min, kcal/s, watts, etc. Heat current, rate of flow of heat, rate of heat transfer, power radiated, power dissipated, etc. are identical terms. Heat current is given by the formula:

$$P = \frac{E}{R} \qquad 1.$$

Notice this is the same as Ohm's law for the conduction of electricity except heat current has units of power which is not true of electrical current. It is for this reason that P is used for heat current instead

of I. Other similarities between thermal and electrical conductivity are striking (see table 1).

heat conduction	electrical conduction
Heat (Q)	Electric charge (Q)
Heat current P = Q/t	Electric current I = Q/t
Thermal resistance R = L/KA	Electrical resistance R = L/kA
Temperature differece E = ΔT (proportional to kinetic energy difference per molecule)	Potential difference E (electric energy difference between two points per coulomb of charge)
Relationship E = PR	Relationship E = IR

Table 1 Comparison of heat and electrical conduction.

Heat current as expressed in equation 1 is usually given in textbooks in the following form:

$$P = Q/t = \frac{KA\Delta T}{L} \qquad 2.$$

Notice there will not be a heat current unless there is a temperature difference. Remember that heat flows from high temperature to low temperature. Table 2 lists the thermal coefficient of conductivities for various materials.

Table 2 Thermal coefficient of conduction.

	Material	kcal/s m C°	Btu in/h ft² F°
Good	silver	0.1	2880
	copper	0.09	2650
	aluminum	0.05	1460
	iron-steel	0.01	350
	lead	0.008	250
Med	ice	0.0005	15.6
	sand	0.0004	12.6
	concrete	0.0004	12.0
	glass (plate)	0.0002	5.5
	water	0.0001	4.3
Poor	wood (varies)	0.00003	0.80
	vermiculite (loose)	0.00002	0.46
	rock wool	0.00001	0.29
	glass wool	0.000009	0.26
	styrofoam	0.000009	0.25
	air	0.000005	0.17
	vacuum	0	0

Example: A 0.5 cm glass plate has an area of 3 m². The outdoor temperature is -20°C and indoor temperature is 22°C. (Surface temperatures must be used which are 18 C° (above outside) and 18 C° (below inside). Find the heat current, thermal resistance and total heat transferred in 12 hr.

Given:
$T_h = 2°C$
$T_C = -4°C$
$K = 0.0002$ kcal/s m C°
$L = 0.005$ m
$A = 3$ m
$t = 12$ h $= 43\,200$ s

Solution: $P = \frac{KA\Delta t}{L}$

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$= (0.0002 \text{ kcal/s m C}^\circ)(3 \text{ m})(6 \text{ C}^\circ)/0.005 \text{ m}$
$= 0.72 \text{ kcal/s}$
$R = E/P = 6 \text{ C}^\circ/0.72 \text{ kcal/s} = 8.33 \text{ C}^\circ \text{ s/kcal}$
or $L/KA = 0.005 \text{ m}/(0.0002 \text{ kcal/s m C}^\circ)(3 \text{ m})$
$= 8.33 \text{ C}^\circ \text{ s/kcal}$
$Q = Pt = (0.72 \text{ kcal/s})(43\,200 \text{ s}) = 31\,000 \text{ kcal}$

Convection:

Convection is the movement of heat by the actual transfer of the hot material (either liquid or gas). A qualitative description of the process is fairly simple. Air or other fluid near the heated object is warmed. It expands and becomes less dense. The buoyant effect on the hot, less dense fluid causes it to rise. Cooler fluid comes in from below and is heated in a continuous isobaric process and a convection current of fluid circulates in the near vicinity.

If the path of the convection current is obstructed, the flow will cease. If the object is producing heat continuously (such as a light bulb), it may overheat. The parts in a TV set would burn out quickly, if the screened bottom were covered.

Forced convection is produced when circulation is created by fans, pumps, etc. Even here, circulation must be unimpaired. An obstructed radiator on a car will soon cause the engine to overheat, for example.

If the inlet and outlet temperatures of a fluid carrying heat away from an object and the rate of flow, density and specific heat of the fluid are known, the amount of heat and the heat current being gained or lost by the fluid can easily be calculated. See the problem sets in module T 2 for several examples. However, the flow of heat away from a heated surface is very complex. Any subject involving fluid flow is complicated.

Heat current when the transfer is by convection of heat away from a hot surface is given by the formula:

$$P = hA(T_h - T_c) \qquad 3$$

Where h is the thermal coefficient of convection, A is the area of the surface (which can be increased by the use of fins, T_c is the temperature of the heated surface and T_h is the temperature of the fluid. The coefficient of convection is the complex part of the formula. It depends on the dimensions and orientation of the surface, difference in temperature between surface and fluid, acceleration of gravity and such fluid properties as the coefficient of viscosity, coefficient of conduction, specific heat at constant pressure, density and the volume coefficient of expansion. Formulas for horizontal, vertical and cylindrical surfaces have been derived and values of h have been determined. See A.L. King, Thermophysics, W.H. Freeman & Co., 1962 chapter 20 for further details.

RADIATION:

Energy is transported by radiation by means of electromagnetic waves. These waves do not require matter to be present as a transporting medium or carrier. In fact, matter such as air, glass, water, etc. that allows the passage of such waves, actually slows down the waves. In a vacuum, heat radiation travels at the speed of light (3×10^5 km/s).

The heat current radiation from the surface of an object depends on the fourth power of the absolute temperature (Kelvin), the surface area (A), and the nature and color of the surface.

$$P = \alpha\sigma AT^4 \qquad 4$$

Where σ is the Stefan - Boltzmann radiation constant (5.67×10^{-8} W/m^2K^4). This equation is known as the Stefan - Boltzmann law of radiation. The symbol α is the absorption factor. The absorption factor depends on the nature and color of the surface. See table 3. The letter A represents the total surface area of the heated object. Radiation can be increased by the use of fins on the object since this would increase the area of the surface.

Material	α
Ideal black body	1.00
Lampblack	0.95
Black lacquer	0.87
Steel, oxidized	0.79
Copper, oxidized	0.72
Brass, oxidized	0.60
Tungsten	0.35
Copper, polished	0.30
Aluminum paint	0.30
Cast iron, bright	0.22
Aluminum, oxidized	0.11
Aluminum, polished	0.04
Silver, polished	0.03
Perfect mirror	0.00

Table 3 Absorption Coefficient

Objects radiate heat according to equation 4. Objects that are good radiators or emitters of heat are also good absorbers of heat. If two objects have the same size, shape and temperature, they radiate or absorb heat according to their absorption coefficient. Black or dark surfaces radiate or absorb better than mirrors or light colored surfaces. See table 3. Lampblack (soot) approximates a perfect black surface while polished aluminum or silver surfaces approximates the perfect mirror. "Silvered" surfaces are used to prevent radiation from a vacuum bottle and some kinds of home insulation. Black paints are used on automobile radiators and electric motors to increase the radiation rates.

An object radiates heat and absorbs heat from its surroundings continuously. Both radiation and absorbtion are given by equation 4. The net rate of flow is given by: $P = \alpha\sigma A(T_o^4 - T_s^4)$ where T_o is the temperature of the object and T_s is the temperature of the surroundings. Notice that radiation would cease only if the temperature drops to absolute zero. Absorbtion would cease if all the surroundings were at absolute zero. The net rate of flow of heat is the difference between the heat radiated and that absorbed. If the object is hotter than the surroundings, it will lose heat. It will gain heat if it is cooler than the surroundings.

Example: A 5 cm steel ball (oxidized) is heated to 500°C. It is suspended in the center of a room at 20°C. What is the net rate at which heat is radiated from the ball? Do not include losses by conduction and convection.

Given: $\alpha = 0.79$
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$
$T_h = 500°C = 773\ K$
$T_c = 20°C = 293\ K$
$d = 5\ cm = 0.05\ m$
$A = 4\pi r^2 = 4\pi(0.025\ m)^2 = 0.00785\ m^2$

Solution: Net rate = rate radiated - rate absorbed
rate radiated = $\alpha\sigma AT_b^4$:
$P = (0.79)(5.67 \times 10^{-8}\ W/m^2K^4)(0.00785\ m^2)(773\ K)^4$
$= 125.5\ W$
rate absorbed:
$P = (0.79)(5.67 \times 10^{-8}\ W/m^2K^4)(0.00785\ m^2)(293\ K)^4$
$= 0.5\ W$
net rate = 125 W = 0.03 kcal/s

A wide band of electromagnetic radiation is radiated by an object. At cool or cold temperatures the principal radiation is in the radio region (longer wavelengths). At hot temperatures the principal radiation is the shorter wavelengths of infrared radiation. At even higher temperatures the principal radiation shifts even more to shorter wavelengths (light and ultra-violet).

NEWTON'S LAW OF COOLING

When conduction, convection and radiation are all involved in transferring heat from an object to its surroundings, the rate of transfer of heat (current) is approximately proportional to the difference in temperature between the object and its surroundings.

$$P = N(T_a - T_s) \qquad 5$$

Where N is a constant depending on the size and shape of the object. T_a is the average temperature of the object and T_s is the temperature of the surroundings. Equation 5 is called Newton's law of cooling and is approximately true provided the temperature difference is not too great.

Example: A house loses heat at a rate of 12 600 Btu/h, when the outside temperature is 20°F. Assuming the house is 65°F, how much heat would be lost per hour when the outside temperature is 0 F?

Given: $T_h = 65°F$
$T_{c1} = 20°F$
$T_{c2} = 0°F$
$P_1 = 12\ 600$ Btu/h

Solution: $N = P/(t_h - t_{c_1})$
$= (12\ 600\ \text{Btu/h})/(65°F - 20°F)$
$= 315\ \text{Btu/h F°}$
$P = N(t_h - t_{c_2})$
$= (315\ \text{Btu/h F°})(65°F - 0°F)$
$= 20\ 500\ \text{Btu/h}$

Note that if N is multiplied by 24 h, it represents the Btu loss per degree-day for this particular house. If the outdoor temperature was above 65°F, flow would be into the house. However, the house temperature is usually taken to be 80°F to calculate cooling requirements. No heating or cooling is required between 65°F and 80°F (outdoor temperatures). The constant N is usually calculated by knowing the area, thickness, insulation, etc. of the walls, ceiling, floors, windows and doors. It can also be determined by using actual fuel usage and weather bureau data for the same period of time.

In the example above, the furnace maintained a constant temperature within the house. Heat losses change only if the outside temperature, winds, etc. change. In the case where no internal heat is produced, the temperature will drop if the temperature of the surroundings is lower than that of the object. Since $P = Q/t$ and $Q = mc\Delta T$ where c is the average specific heat of the object, equation 5 can be written (after substitution):

$$\Delta T = n(T_a - T_s)t \qquad 6$$

Where ΔT is the change in temperature, t is the time and n is a constant ($n = N/mc$).

Example: A cup of coffee cools from 180°F to 160°F in 2 min in a room where the temperature is 70°F. How much time would be required for it to cool from 120°F to 100°F?

Given: $\Delta T_1 = 20°F$
$T_{a1} = 170°F$
$T_{a2} = 110°F$
$T_s = 70°F$
$t_1 = 2\ \text{min}$
$\Delta T_2 = 20°F$

Solution: $n = \Delta T_1/(T_a - T_s)t$
$= 20°F/(170°F - 70°F)(2\ \text{min})$
$= 0.1/\text{min}$
$t_2 = \Delta T/n(T_a - T_s)$
$= 20°F/(0.1/\text{min})(110°F - 70°F)$
$= 5\ \text{min}$

Cooling proceeds rapidly when the temperature of the object is higher than that of the surroundings and much slower as its temperature approaches that of the surroundings. See figure 2. Temperature S is the temperature of the surroundings. Newton's

law of cooling also applies to objects that are colder than the surroundings. In this case the object warms up instead of cooling. Remember that Newton's law of cooling only applies if the temperature difference is not too great.

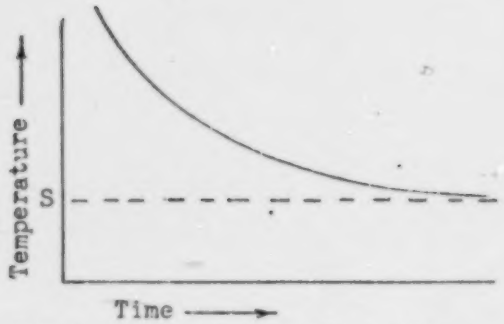

Fig 2 Newton's law of cooling

REPORT

Module T 3 TRANSFER OF HEAT

The following report should be completed by students in various technologies as required by the instructor.

Heat is produced whenever work is done against the force of friction, in the churning of turbulant flow, in the flexing, cutting or grinding of elastic materials, during combustion, by electric currents and by nuclear reactions.

I. Make a list of three (3) very specific examples of devices or equipment used in your technological field in which heat is produced by any of the methods described above. These should be devices or equipment in which the heat produced must be carried or transferred away to keep it working properly and efficiently. Give examples in which the heat transfer is accomplished mainly by conduction.

Conduction

A. Describe:

1. The device or equipment. Include a drawing or diagram of the device or paste in a picture from a magazine or newspaper.

2. How the heat is produced. Tell what parts are rubbing against each other or what parts have electric currents in them or what fuel is being burned, etc.

3. What would happen to the device if the heat is not transferred away.

4. The heat path along which the heat is conducted. Describe the material used for the heat path.

5. The heat sink to which the heat is transferred. NOTE: The heat sink may be an intermediate device such as a fin or other metal equipment. Do not trace the heat flow beyond this point even though the eventual heat sink may be air in a room, the atmosphere or outer-space.

II. Repeat part I, except describe examples (three) of equipment from which the heat is transferred mainly by convection.

III. Repeat part I, except describe examples (three) of equipment from which the heat is transferred mainly by radiation.

References and sources of information

1. Laboratory or shop equipment
2. Textbooks, shop manuals, etc.
3. Lab, shop and theory instructors are good sources of information

PROBLEMS

Module T 3 TRANSFER OF HEAT

1. What is the green-house effect? Explain why an automobile with closed windows gets much warmer inside than the outside air. How does a solar collector work?

2. Why should plates and cups with metalic or dark decorative markings not be used in a microwave oven?

3. Some objects you touch seem to feel cooler than others even though they are at the same temperature. (Touch the metal and wooden parts of your desk or table, for example). Explain why.

4. On a very cold day, a moistened finger will freeze to a piece of metal but not to a piece of wood. Explain why.

5. Each of the following statements are false. Explain why.

   a) Convection can take place only in gases.
   b) Heat transfer occurs between two bodies only when one is a better conductor than the other.
   c) At 100°C, a kilogram of water contains more internal energy than a pound of lead. If the lead was placed in the water, heat would immediately be transferred from the water to the lead.
   d) Black bodies are the best emitters of heat energy but silvered ones are the best absorbers. Hot air ducts and thermos bottles are silvered so heat is absorbed from the surroundings to keep the air or coffee hot, respectively.

6. Which of the following could be used for units of heat currents? (a) joules, (b) horsepower, (c) calories, (d) Btu/h, (e) ft lb, (f) kcal/s, (g) kilowatt hour, (h) watts

7. An automobile has 1 m^3 of side glass 0.5 cm thick. The inside temperature averages 20°C and the outside temperature is -20°C. Assume the inside surface temperature is 0°C and the outside surface temperature is -1°C. Find the heat current through the side glass. (K = 0.0002 kcal/s m C°).

8. The automobile of problem 7 has 0.8 m^2 of windshield 0.6 cm thick. If the inside surface temperature is 10°C and the outside surface temperature is 9°C find the heat current. Find the heat current through the back window if it is the same size as the windshield but surface temperatures are 0°C and -1°C. (K = 0.0002 kcal/s m C°).

9. If the automobile of problems 7 and 8 was moving would you expect the outside surface temperature of the glass to change? If so, in what way and why? If the outside surface temperature decreases, what will happen to the inside surface temperature.

10. In the summer time, the inner surface temperature of windows (problem 7) is less than the outside surface temperature. What changes in inner and outer surface temperatures would you expect if the car started to move? Explain in detail.

11. What is the purpose of the groove cut around the circumference of a piston between the piston head and the top ring groove. What is the purpose of horizontal slots cut in the piston just below the bottom ring groove? See diagram.

12. An aluminum piston head has a temperature of 450°F and the temperature just below the bottom (oil) ring groove is 260°F. If the distance between these two points is 1.2 in and a one-inch wide section on the front of the piston has a least cross-sectional area of 0.1 in^2, find the heat current by conduction. (The least area is in the section behind the bottom (oil) ring groove with its oil ports). NOTE: Not all the heat travels this path. Part of it is diverted through the rings to the cylinder wall and to the cooling system.

13. The lower part of the piston skirt is at a temperature of about 230°F. Would you expect very much heat transfer between this part of the piston and the cylinder wall? Why?

14. The vertical section of the exhaust pipe on a diesel truck is 10 cm in diameter and 1.75 m long. If the temperature of the pipe is 120 C and the ambient temperature is 30 C find the amount of heat removed per second from it by convection. Assume the truck is not moving (no wind). The coefficient of convection is given by the formula: $h = 1.42\ (\Delta T/L)^{0.25}$ W/m C°. NOTE: $x^{0.25}$ means square root of the square root.

15. What is the net rate of heat flow from the exhaust pipe in problem 14 by radiation. The absorbtion factor is 0.75. NOTE: x^4 means square of the square.

16. A light truck is traveling 50 mi/h on a day when the outside (ambient) temperature is 45°F. The temperature of the coolant at the radiator inlet is 160°F (170°thermostat) and at the radiator outlet it is 120°F. If the pump moves the coolant at a rate of 11.25 gal/min and it has a density of 8.8 lb/gal, find the amount of heat removed by the air stream through the radiator each minute. The specific heat of the coolant is 0.8 Btu/lb F°.

17. If all the heat lost by the radiator in the previous problem is absorbed by the air passing through it, find the rate of flow of the air in cubic feet per minute. The temperature of the air goes from 45°F to an average of 130°F as it passes through the radiator. Its average density is 0.069 lb/ft^3 and its specific heat is 0.24 Btu/lb F°.

18. Normal temperatures during a hard braking on an automobile is about 260°C created on the inner surface of the brake drum. A 2000 kg automobile traveling at 95 km/h must dissipate most of 2156 kcal of heat in the four brake drums. The faster the stop, the faster the heat is produced in the drums. About one-fourth of the energy is dissipated by each front wheel and one-fifth by each back wheel. The rest is dissipated directly into the turbulant air around the vehicle and in tire flexing while the car is stopping. At the moment the car comes to a stop, assume the outer surface of the cast iron and steel drums have a temperature of 100°C. Find the heat current at that moment if each drum has 0.06 m^2 of surface area and is 1 cm thick. NOTE: As soon as the car is stopped, no more heat is produced so the temperature of the inner surface decreases while that of the outer surface increases. They then have a fairly uniform temperature of about 170°C - 180°C. Heat is dissipated by radiation and convection from the outer surface. Some of the heat is conducted through the brake lining and brake shoe to the backing plate. Some is conducted from the drum toward the hub. If the car begins moving again, the heat is rapidly carried away by air currents. Some brake drums have fins to aid the transfer of heat.

19. A diesel engine on an irrigation pump has an average temperature of 180°F when it is shut off. It cools to 175°F in 5 min. How long will it take to cool from 140°F to 130°F? The outside temperature is 85°F.

20. How long will it take the engine in the previous problem to cool from 110°F to 100°F? From 100°F to 90°F?

21. What is a heat exchanger? Exactly what do they do? Give four examples of where they might be used in which the transfer of heat is from (1) gas to gas, (2) gas to liquid, (3) liquid to gas, and (4) liquid to liquid.

22. Match each numbered word with a lettered word: A radiation, B conduction, C insulation, D convection.

1.	Fin	7.	Copper
2.	Fan	8.	Styrofoam
3.	Black paint	9.	Solid
4.	Silvered surface	10.	Liquid
5.	Silver metal	11.	Gas
6.	Vacuum	12.	Metal

ANSWER KEY (PROBLEMS)

Module T 3 TRANSFER OF HEAT

1. Radiation from the sun is transmitted through glass, plastic, etc. It is absorbed by objects inside greenhouse, car, solar collector, etc. It reradiates as a longer wavelength of radiation which is not transmitted by the glass. Thus the internal temperature increases.

2. They absorb more radiation than the rest of the container. Temperature increases with accompanying differential expansion and breakage.

3. Heat is conducted away, rapidly by metals so heat flow continues from your hand giving the sensation of coolness. Heat piles up on surface of non-conductor so heat transfer decreases.

4. See question 3.

5. a) Liquids to but not solids
   b) Only when there is a temperature difference
   c) At the same temperature there would be no heat transfer.
   d) Black bodies are good emmitters and good absorbers. Silvering is used to prevent radiation losses.

6. Heat: a,c,e,g. Heat current: b,d,f,h.

7. 2.4 kcal/min

8. 1.6 kcal/min, 1.6 kcal/min

9. Decrease, air currents carry away warmer air layers near surface so the temperature difference is greater, decrease, also.

10. Increase, air currents carry away cooler air layers near outer surface so the temperature difference is greater.

11. Reduces cross-sectional area the heat can travel through and acts as a heat dam. Eliminates heat conduction path to the piston skirt, thus reducing thermal expansion effects.

12. 160.5 Btu/hr

13. Not much. No metal to metal contact. Oil film between them. Little temperature difference between piston skirt and lower cylinder wall. Heat is removed by oil from skirt.

14. 188 W

15. 361 W

16. 3190 Btu/min

17. 226 ft^3/min

18. 9.60 kcal/s

19. 18.5 min

20. 46.3 min, 92.5 min (assuming outside temperature hasn't changed).

21. A device which conducts heat through a thin metal wall from one fluid to another. 1. Refrigerator condenser or gas furnace, 2. Hot water heater, 3. Car radiator, 4. Water cooled oil on hydraulic pumps, dynamometers, etc.

22. A: 1,3,4
B: 5,7,9,12
C: 6,8
D: 1,2,10,11